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STATUS AND TRENDS IN CONCENTRATIONS OF CONTAMINANTS AND MEASURES OF BIOLOGICAL STRESS IN SAN FRANCISCO BAY

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NOTICE

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INTRODUCTION

Under the National Status and Trends (NS&T) Program, the National Oceanic and Atmospheric Administration (NOAA) monitors the occurrence of certain contaminants and indicators of biological stress at approximately 200 sites in the United States. This Program was initiated in 1984 to provide an internally consistent data base for assessing the condition of parts of the Nation's coastal and estuarine environments. The Program thus far has focused largely upon generation of chemical contaminant data for sediments, fish, and bivalves, and certain analyses of these data. The results of the initial analyses are summarized in progress reports (NOAA, 1987a and b).

The objectives of this report are to: (1) portray geographic trends in the concentrations of contaminants and the prevalence of selected measures of biological effects; (2) portray temporal trends in concentrations of contaminants and prevalence of selected measures of biological effects; (3) relate selected measures of biological effects to the concentrations of contaminants; and (4) compare the trends observed in available historical data to compatible recent measurements made by NOAA in San Francisco Bay. These objectives will be met through evaluation of data collected by NOAA and the many others who have studied the conditions in San Francisco Bay. Some of the data from the NOAA NS&T Program will be reported for the first time in this report.

The intent of this report is to document certain conditions in San Fracisco Bay as they were determined through surveys and research performed by many organizations, including NOAA. The intent is not to attribute the status and trends in conditions of the system to causes or sources.

The report focuses upon contaminants and certain measures of biological stress thought to be caused by these chemicals. The chemical analytes for which the data are evaluated are among those that are quantified in the NS&T Program and known to be potentially toxic to marine and estuarine organisms. Specifically, they include selected trace metals (mercury [Hg], cadmium [Cd], copper [Cu], silver [Ag], lead [Pb], and chromium [Cr]), PCBs, DDT and its derivatives, and total polynuclear aromatic hydrocarbons (PAHs). The report will summarize the results of analyses of surficial sediments and biota (specifically, bivalves and fish). The measures of biological effects will include prevalence of toxic sediments as determined in sediment bioassays, prevalence of histopathological disorders in fish, and certain measures of impaired reproductive success in starry flounder and striped bass. These biological effects have either been measured in studies supported by NOAA or are under consideration for future use in the NS&T Program. One chapter of the report is devoted to each of the chemicals and types of biological effects.

The initial intent was also to evaluate benthos community data to determine spatial and temporal trends relative to concentrations of contaminants. However, many of the data sets produced in benthos studies in San Francisco Bay have not included synoptic measures of contaminants, and a wide variety of sampling and data analysis methods have been used in these studies (Hopkins, 1986), confounding any attempts to draw conclusions on a broad geographic scale. Additionally, numerous natural factors are known to cause remarkable changes in the benthos that may exceed or mask changes attributable to contaminants. Thus, the benthos data have been excluded from this report.

The report addresses the San Francisco Bay system (referred to hereafter as "the Bay"), including Suisun Bay/Carquinez Strait, San Pablo Bay, central Bay, and south San Francisco Bay (Figure 1). These areas are referred to as "basins" in the report. Data are presented for each of these four basins along with those from peripheral harbors and waterways. The Suisun Bay/Carquinez Strait basin includes those waters east of the Carquinez Strait Bridge to Antioch. The San Pablo Bay basin includes those waters west of the Carquinez Strait Bridge to a line drawn between Point San Pedro and Point San Pablo. The basin in the center of the system (referred to hereafter as central Bay) includes those waters between a line drawn from Point San Pedro to Point San Pablo south to the Oakland/Bay Bridge and west to a line drawn from Point Bonita to Point Lobos. The "south Bay" basin includes those waters south of the Oakland/Bay Bridge. Areas such as the Mare Island Strait, Richmond Harbor channel, Oakland inner and outer harbors, Islais Creek Waterway, China Basin, and Redwood Creek are not included in these basins. Rather, they are treated separately as peripheral harbors and waterways, and referred to in the report as the "periphery" or "peripheral areas." Data from nearby Bodega Head, Bodega Bay, and Tomales Bay are used as reference areas (relatively uncontaminated areas) for comparison with data from the San Francisco Bay system.

Data were acquired from many helpful colleagues in state, local, and Federal agencies; universities; and consulting firms. Their helpfulness and interest in the report is greatly appreciated. Data from refereed journal articles, technical reports, contractor reports, and progress reports were used. The data in these reports were of varying quality and detail; however, they were accompanied by sufficient information on sampling and analytical methods to warrant inclusion of the data in this synthesis report. Reports in which the data were presented only in summarized form (i.e., individual data points were not available) were generally not used.

As a part of the nationwide grid of sampling sites, nine sites in San Francisco Bay and a site each in nearby Tomales Bay, Bodega Bay, and Bodega Head are being sampled annually (Figure 2). This report presents some of the results from those sites and compares them with data collected by others in the region. Regional reports on other geographical areas are expected to be prepared in future years.

The report includes data from the Benthic Surveillance Project (BSP) of the NS&T Program; this Project conducted by NOAA's National Marine Fisheries Service (NMFS) has sampled four sites (eastern San Pablo Bay, Southhampton Shoal, off Oakland, and off Hunters Point) in the Bay and a site in Bodega Bay annually since 1984 as a part of the grid of Pacific Coast sites (Figure 2). Data are produced annually for contaminant concentrations in bottomfish and sediments and for prevalence of certain histopathological conditions in the fish.

The report also includes data from the Mussel Watch of the NS&T Program. Beginning in 1986, chemical analyses of resident mussels (*Mytilus edulis*) have been performed annually on samples from two sites (San Mateo Bridge and Dumbarton Bridge) in the Bay and a site each in Tomales Bay (*M. edulis*) and at Bodega Head (*M. californianus*). Mussels were not present at two other sites in the Bay, off Semple Point and off Point San Pedro. An additional site was added east of Yerba Buena Island in 1987; the data are not included in this report. Data from sediments collected from four of the five Mussel Watch sites in the Bay (sediments from the Dumbarton Bridge site have not been analyzed thus far) and one in Tomales Bay are also included in this report. Sediments collected at a site near Bodega Head also have not been analyzed thus far.

In addition to its NS&T Program monitoring activities in the San Francisco Bay area, NOAA has supported several investigations of the quality of sediments in the Bay and the effects of contaminants on the health and reproductive success of selected species of fish. Also, NOAA has elected to use San Francisco Bay for testing and development of new environmental assessment tools for future use in its NS&T Program. A variety of candidate methods are being evaluated based upon their sensitivity to toxic chemicals found at selected locations in the Bay area. Some of these methods may be used in forthcoming regional assessments or surveys elsewhere in the country and/or in nationwide monitoring. A separate report on these investigations will be available in 1988.

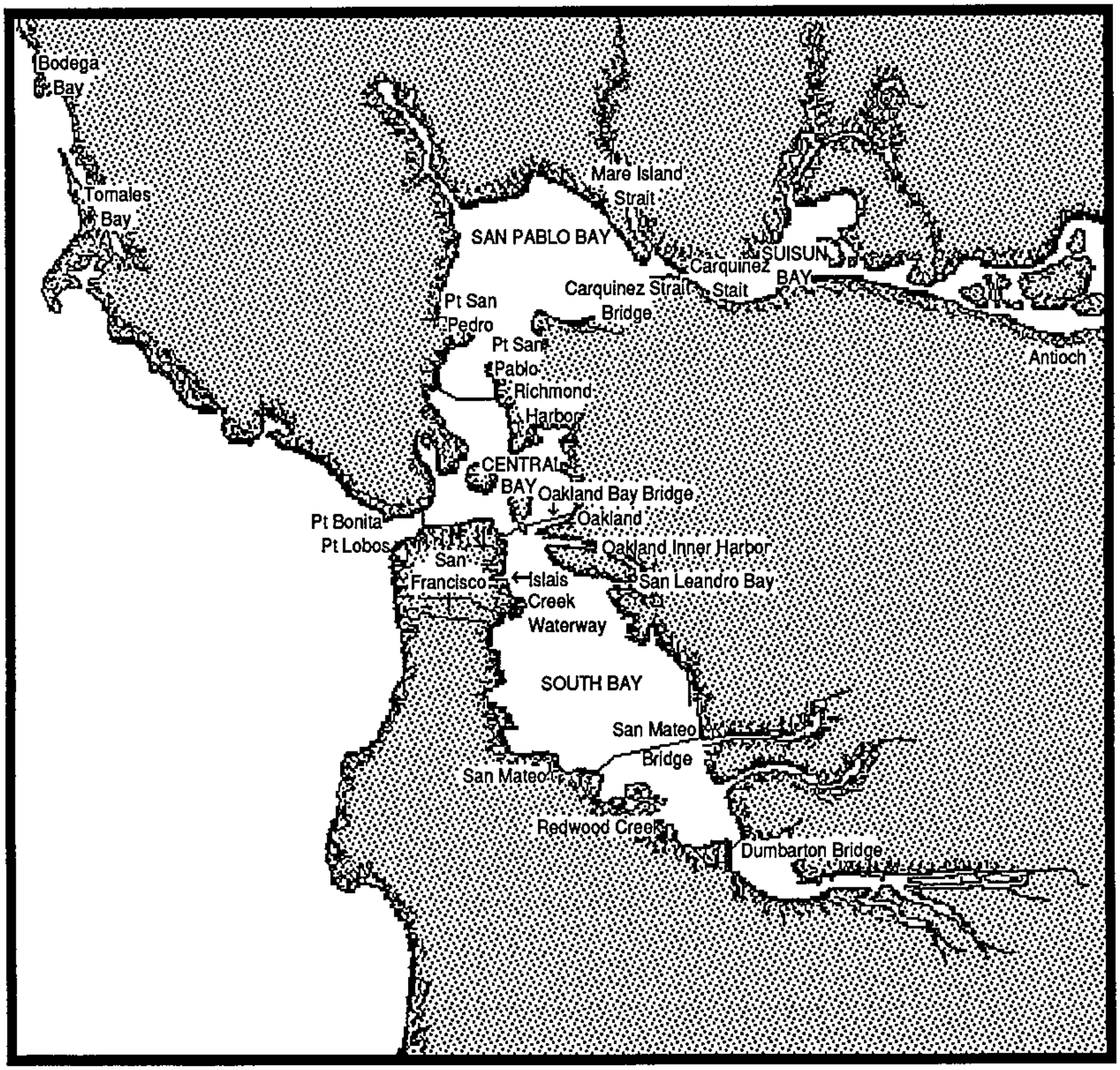

Figure 1. Major geographic place names used in this report.

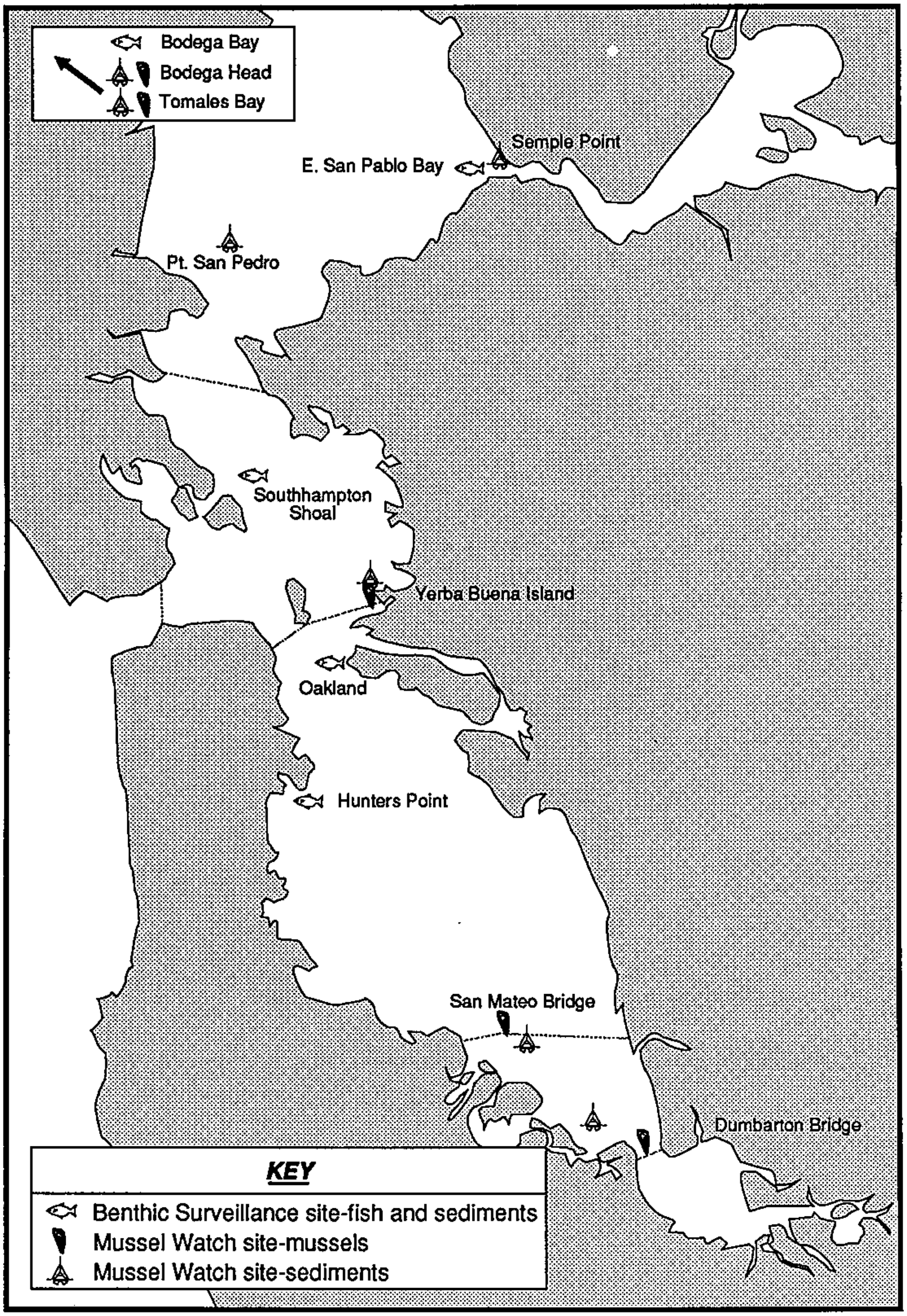

Figure 2. Location of NOAA NS&T Program sampling sites in San Francisco Bay.

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METHODS

A. Approach

The data compiled for this report were obtained from numerous investigators, each of whom had their own goals to satisfy. These various goals led to differences in sampling methodologies which, coupled with changing laboratory methods over the years, added to the variability in the resulting data due to natural environmental factors. Since no standardized analytical protocols have been adopted for use in the Bay, any attempt to summarize and merge data from various studies is severely handicapped. The use of different methods by various investigators may have resulted in incomparable data which, when merged together, may indicate spatial or geographic trends that do not actually exist. No Bay-wide survey and monitoring of contaminants or measures of effects have been conducted recently in the Bay with state-of-the-art methods. A survey conducted in 1970 of three trace metals in sediments is the only study that approached being a synoptic assessment on a Bay-wide scale. The methods used then are now considered to be semiquantitative.

The overall approach taken in this report was to use a preponderance of evidence from individual investigations to determine geographic and temporal trends in contamination and biological effects. Then, corroborate (or refute) those trends with pooled (merged) data.

To determine geographic trends in contaminant concentrations and incidences of measures of effects (Objective 1), data available from the various parts of the Bay were compared. Where sampling protocols and replication in individual studies allowed, the data from sampling sites or areas were transformed to base 10 logarithms and were compared using analyses of variance (ANOVA), followed by Scheffé's F-test, or when only two sites were compared, a t-test was performed on the transformed data. All statistical tests were conducted on a Macintosh Plus ™ computer, using Statview 512+, version 1.0 (© Abacus Concepts, Inc.) software. Where no replication was used by the investigators, statistical tests were not performed and the analytical results were simply compared arithmetically. In those cases, no conclusions regarding between-site differences could be reached. No statistical analyses were performed with data from different studies because of the variability in methods between studies. Data from individual sites and studies were pooled for major geographic areas: major basins and peripheral areas of the Bay. This data pooling step was undertaken to provide an overview of broadscale geographic trends, if any, using as much data as possible. Means, ranges, and standard deviations were usually calculated for the major basins and peripheral areas. These values must be used with caution, however, since different methods may have been used by the various investigators. Overall mean values from the pooled data sets were compared with recent NS&T Program data from many sites along the Pacific Coast.

Data have been collected sporadically in an inconsistent manner in the Bay. Most studies have focused upon only selected portions of the system. An investigation, for example, that encompassed Richmond Harbor may have been followed the next year by a study of only parts of the San Francisco shoreline in the south Bay basin. Therefore, the pooled mean values for the basins are to be treated very cautiously. The location of individual sampling sites within each basin provided varying representation of conditions within each respective basin or peripheral area. The proportion of sites within a basin or peripheral area that were from clean sites and contaminated sites was not consistent. The number of samples taken over the years in each area and basin differed. Therefore, the degree of contamination of one basin or area may be exaggerated or underestimated, depending upon the location of sites within the basin or area.

To determine temporal trends in contamination and biological effects (Objective 2), data from investigations by individual agencies or investigators that used apparently consistent methods were sought and used when available. Strongest evidence of temporal trends would likely be attainable by using internally consistent methods applied to samples taken with the same methods from the same sites at succeeding sampling dates. These data, which are not available for all analytes, were supplemented by examination of merged data sets, but the latter approach is clearly much weaker and susceptible to error. Since very little monitoring is conducted in the Bay expressly to determine temporal trends in contamination and biological effects, little reliable, internally consistent data exist.

No accepted thresholds or criteria for contaminant concentrations exist to judge the level of chemical concentrations that are a biologically damaging excess. Therefore, empirical observations of contaminants and effects must be made synoptically in the field. To determine relationships between contaminant levels and occurrence of biological effects (Objective 3), reports were examined and investigators were interviewed to determine what types of effects had been observed in the Bay. Reports from these investigations were studied to determine if contaminant data had been collected synoptically and if the data covered a sizable portion of the Bay. Also, the reports were examined to determine if the measures were of potential interest to NOAA as candidates for future use in the NS&T Program. The data from the biological and chemical measures were compared using regression analyses and other methods described in the text. Also, the contaminant levels associated with modes of frequency of occurrence of some biological effects were determined in a rank order analysis where the data were available.

The comparability of site-specific trends observed in available historical data with those from recent measurements made by the NS&T Program (Objective 4) was tested by simply extending historical trend analyses with the more recent measures from the same sites and determining if the direction of historical patterns continued with the new data. Furthermore, the NS&T Program data were compared to the means and ranges in historical data from respective basins to determine if the NS&T Program sites were representative of conditions within the basin. If the means of the NS&T Program values were within an arbitrarily selected factor of 2 or less of the historical mean for the respective basin, the NS&T Program site was considered to be representative.

Contaminant concentrations in this document are reported in dry weight (dw) units, since most of the data that were available were given in those units. Where data (usually those for biota) were reported only in wet weight (ww), the values were converted to dw by using the moisture data provided. Where no moisture data were provided to facilitate this conversion, the average moisture content from other surveys of the same species was used.

For those data that were reported as less than the detection limits, a value of half the reported detection limit was used in the calculation of means. The detection limits varied considerably for some analytes within and between data sets.

B. Sources of Data

A varying number of chemicals has been measured by various investigators who have studied the Bay. The sources of data for sediment and the analytes quantified are summarized in Table 1. The majority of the contaminant data from sediments is from dredging studies conducted by the U.S. Army Corps of Engineers (COE). They were obtained for Hg, Cd, Cu, Pb, Cr, Ag, DDT, and PCB in the "Dredge Disposal Study for San Francisco Bay and Estuary" Appendices B, D, F, and H (COE, 1979a) supplemented by unpublished dredging data sheets for 1975, 1976, 1977, 1978, and 1979 (COE 1975-1979). In most of these studies, only the trace metals were measured. Other data from dredging studies included those from the draft and final environmental statements for Oakland Outer Harbor (COE, 1979b), Oakland Inner Harbor (COE, 1983), Alameda Naval Air Station (NAS) (COE, 1973), and the *U.S.S. Missouri* Homeporting Study at Hunters Point, Treasure Island, and Alameda (U.S. Navy, 1987 and ESA, 1987). DDT was measured in Lauritzen Canal by Frizzell and Davies (1986) for the Regional Water Quality Control Board (RWQCB).

Additional data for sediments were obtained from studies of sewage and industrial discharges from parts of the Bay (CH^2M-Hill, 1979, 1981; Kinney and Smith, 1982; Stevenson et al., 1987). Data from research projects sponsored by NOAA have included measures of sediment contamination at many sites in the Bay (Chapman et al., 1986; Spies et al., 1985a and b; personal communication, 1987). The NOAA NS&T Program has developed data for nine sites in the Bay and a sediment sampling site each in Tomales Bay and Bodega Bay (NOAA, 1987a and b; Boehm et al., 1987). The U.S. Environmental Protection Agency (EPA) measured contaminants at sites in south Bay in 1986 (Baumgartner et al., unpublished manuscript). The U.S. Geological

Survey (USGS) has sampled many parts of the Bay and quantified selected trace metals (e.g., Luoma et al., 1984, 1987; Peterson et al., 1972).

The only data available thus far to determine temporal trends in contamination of sediments are those from repeated dredging studies in selected harbors (COE, 1975-1979 unpublished data sheets; 1979a, b) and the South Bay Dischargers Authority (SBDA) studies from 1982 through 1986 (Stevenson et al., 1987). These data were compared over the period during which measurements were made and plotted. Comparisons of data from different studies performed in different years were complicated by the fact that different sites were often sampled to meet the individual goals of the studies. The data developed thus far by the NOAA NS&T Program are for only a 2-year period (Benthic Surveillance Project) and a 1-year period (Mussel Watch), precluding determinations of trends.

Data for biota in the Bay have been collected in over 20 different surveys or programs, most of which performed sampling only once. A wide variety of bivalves and fish have been collected along with a few species of crustaceans. The analytes measured in these biota varied among the different surveys (Table 2). Additional surveys measured only the concentrations of DDT (see Chapter 10).

The U.S. EPA (Shimmin and Tunzi, 1974) sampled oysters (*Crassostrea gigas*) or clams (*Mya arenaria* or *Tapes semidecussata*) from 16 sites in San Francisco Bay and from a site in Drake's Estero in 1972. Between 1972 and 1976, the National Pesticide Monitoring Program (NPMP) sponsored by the U.S. EPA sampled striped bass (*Morone saxatilis*), bay anchovy (*Anchoa mitchiilli*), English sole (*Parophrys vetulus*), shiner perch (*Cymatogaster aggregata*), longfin smelt (*Spirinchus thaleichthys*), Delta smelt (*Hypomesus transpacificus*), and Pacific sanddab (*Citharichthys sordidus*) from two sites in the Bay (Butler and Schutzmann, 1978).

Between 1973 and 1975, Anderlini et al. (1975a and b) sampled bivalves (*Macoma balthica, Mytilus edulis, Macoma nasuta, Crassostrea gigas*) at 30 sites in San Francisco Bay. Girvin et al. (1975) sampled clams (*Mya arenaria, Tapes japonica*) or bay mussels (*Mytilus edulis*) or oysters (*Ostrea lurida*) or the mussel *Ischadium demissum* from seven sites in the Bay in 1975. In 1976, Risebrough et al. (1978) sampled mussels (*Mytilus edulis*) from 29 sites in the Bay. Between 1976 and 1978, the U.S. EPA conducted three annual surveys of mussels (*M. edulis*) from nine sites around the Bay (Farrington et al., 1982). During the same years, Bradford and Luoma (1980) surveyed bivalves (*Macoma balthica* or *Tapes japonica*) from five sites in the Bay. In 1979, CH2M Hill (1979) sampled bivalves (*Tapes japonica*) and English sole (*Parophrys vetulus*) and staghorn sculpin (*Leptocottus armatus*) from eight sites in the south Bay. In 1980, the California State Water Quality Control Board (McCleneghan et al., 1982) sampled clams (*Tapes japonica* or *Mya arenaria*) or bay mussels (*M. edulis*) from 10 sites around the Bay. The same year, clams (*Tapes japonica*) from three east Bay sites were sampled by the East Bay Municipal Utility District (Kinney and Smith, 1982).

The California Mussel Watch Program sampled resident Bay mussels (*M. edulis*) or coastal mussels (*M. californianus*) transplanted to as many as 32 sites in San Francisco Bay. They also sampled resident *M. californianus* annually at Bodega Head. These transplanted mussels were analyzed after varying periods of exposure (usually 4-6 months) at each site. Sampling has been conducted annually at many of the sites since 1979. Luoma et al. (1984, 1987) sampled *Corbicula* sp. in Suisun Bay from 1983 through 1987 for selected metals. Beginning in 1984, the NOAA NS&T Program has measured contaminants in the livers of starry flounder (*Platichthys stellatus*), white croaker (*Genyonemus lineatus*) and English sole (*Parophrys vetulus*) from four sites in the Bay and a site in Bodega Bay. That Program has also sampled resident mussels (*M. edulis*) from two sites in the Bay and a site each in Tomales Bay and at Bodega Head annually since 1986. A third site near Yerba Buena Island was added in 1987.

Additional sources of data on biological samples include those of Cain and Luoma (1985), who sampled *Macoma balthica* transplanted to two sites in the south Bay in 1978. Foe and Knight (1986) sampled *Corbicula* spp. in Suisun Bay in 1981 and Wyland (1975) sampled *Mytilus edulis* or *M. californianus* or *Modiolus demissus* or the clams *Ruditapes semidecussata, Mya arenaria* or *Macoma nasuta* from three sites in the Bay and in Tomales Bay in 1974. In addition, Luoma and colleagues from the USGS have conducted numerous surveys of bivalves (generally clams) in San Francisco Bay and have published summarized results in many articles (see, for example, Luoma et al., 1985). The sources of data for measures of biological effects are discussed in the individual chapters on effects. Most of the studies that produced biological effects data also produced synoptically collected chemical data.

A considerable number of place names is used in the report. The locations of many are shown in Figures 1 and 2. The names are those assigned by the original investigators and their reports should be checked for exact locations.

C. Sources of Variability in Data

All the data summarized in this report are subject to different sources of variability. All were collected with the hope that they would be representative of conditions in the particular part of the Bay that was sampled. But each data point can be affected by sampling protocols, analytical methods, and natural factors.

Sampling protocols for sediments differed among the various investigations performed in the Bay. Though only data for surficial sediments were used in this document, a variety of definitions of "surficial" has been used. Surficial sediment samples have been collected that were 1 cm, 2 cm, 6 inches, and 2.5 feet, 25 feet, etc., thick. Some have been collected to the bottom of the oxidized layer, whatever its thickness. In this report, data from the upper 1 cm to 2.5 ft. were used. Sampling equipment varied from piston corers to grab samplers; the data were used regardless of the type of sampling device.

The most important difference in sampling methods for the biota involved transplanted versus resident mussels. Transplanted mussels were usually *Mytilus californianus* collected at Bodega Head and deployed at the sampling sites in the Bay for specified periods of time on buoyed, anchored arrays. Much of the data for the Bay are from analyses of these transplants. However, there is a considerable amount of data from analyses of resident *M. edulis.* While the data in Hayes et al. (1985) and in this document show good comparability between residents and transplants at the same sites, the data are, nevertheless, for two different species that "sampled" the environment for different periods of time. The data from both species are pooled in this report.

Analytical methods used in chemical analyses have changed remarkably in the past 15 years, since contaminant analyses began in the Bay. Only trace metal analyses were performed with samples collected in the early 1970s and methods used then are now considered to be semiquantitative. Analyses for DDT and PCBs were performed beginning in the mid 1970s. However, few analyses for a broad suite of organic compounds such as aromatic hydrocarbons and pesticides were performed until the late 1970s and mid 1980s. Methods used in organic chemical analyses have changed and evolved in the past 10 to 15 years. The data summarized in this document are from many investigators and laboratories and are subject to inter-laboratory differences in analytical methods. The data are also subject to changes in methods with time at any particular laboratory as personnel changed and procedures and equipment evolved. As a result, apparent trends in concentrations of contaminants may merely reflect differences or changes in methods. Therefore, the approach taken in this report initially was to examine data from each study individually where it was hoped that the methods were internally consistent. Then, the data were gradually pooled from many studies to substantiate the trends seen in each individual study with the larger pooled data set. A preponderance of evidence from individual studies was expected to indicate possible trends in contamination.

No consistent analytical protocols have been developed for use in the Bay by all investigators. It is difficult to determine which of the methods is "correct," and therefore, which provides the best data that represent conditions in the Bay. This document uses data from most of the studies that have been performed in the Bay. Few data sets have been excluded. Data from studies in which the methods were not described, or inadequately described, or were clearly very poor, were excluded.

A wide variety of natural or environmental factors can affect the concentration of contaminants in sediments and biota. In sediments these factors include texture (grain size), minerology, organic carbon content, salinity, oxidation-reduction potential, presence and activity of burrowing animals, depth and scouring/erosion processes. The bioavailability of sediment-associated contaminants can vary remarkably with many of these factors, but is obscured in chemical analyses by use of strong acids or solvents to extract the contaminants for quantification. Fine-grained sediments with high surface area-to-volume ratios often attract the highest contaminant levels. Because fine-grained sediments have a very low specific gravity, they tend to accumulate only in areas with low water currents and no scouring of the bottom. Therefore, high contaminant levels are usually found in the protected low-energy areas with high percent fine-grained sediments. However, this generality may be violated in places where local sources of contaminants may exist nearby. Most chemical analyses of sediments in the Bay were not accompanied by analyses of these "normalizing" factors that may affect contaminant concentrations. Therefore, there is no way to account for differences in contaminant concentrations in those data sets. Some surveys, however, did include tests for texture and/or organic carbon. The relationships observed in the data from the Bay between contaminant concentrations in sediments and various sedimentological properties are illustrated and discussed in Chapter 16.

In biota, natural sources of variability include lipid content, age, sexual maturity, trophic level, and feeding method. Animals that have high lipid (fat) content generally accumulate relatively high levels of lipophilic organic compounds. Since lipids are often expelled in reproductive products (eggs, sperm) following their accumulation during gametogenesis, the contaminant concentration in an animal can change remarkably following spawning. Some organic compounds may accumulate and remain in the tissues of animals as they grow older, leading to higher concentrations in relatively old animals. Contaminants are picked up by biota from several routes of exposure, the most important of which in marine systems is often the food. Since the type of food varies among species and the affinity of contaminants varies among prey or food items, some animals can be expected to ingest more contaminants than others due solely to their feeding habits. For example, deposit-feeding bivalves may accumulate more contaminants than suspension- or filter-feeding species. Benthivorous bottom fish may accumulate more contaminants than planktivorous pelagic fish. The relationships observed in the data from the Bay between contaminant concentrations in the biota and various biological properties of the biota are illustrated and discussed in Chapter 16.

Note that data are presented for the Japanese littleneck clam. Individual investigators have variously referred to the species as *Tapes japonica, Tapes semidecussata,* or *Ruditapes semidecussata* as its name has changed over the years.

Table 1. Sources of sediment contamination data from San Francisco Bay used in this report..

Authors	Sponsor	Sites Sampled	Hg	Cd	Cu	Pb	Cr	Ag	PAH	DDT	PCB
CH2M-Hill, 1979	San Francisco	23	x	x	x	x	x	x		x	x
CH2M-Hill, 1981	Chevron USA	21		x	x	x	x			x	x
Kinney & Smith, 1982	EBMUD	30		x	x	x	x	x		x	x
Boehm, et al., 1987	NOAA	5	x	x	x	x	x	x	x	x	x
Chapman, et al., 1986	NOAA	3	x	x	x	x	x	x	x	x	x
NOAA, 1987a	NOAA	4	x	x	x	x	x	x	x	x	x
Spies et al., 1985, pers. comm.	NOAA	29		x	x	x	x		x	x	x
Luoma et al., 1984	USGS	10		x	x	x		x			
COE, 1972-1979	COE	611	x	x	x	x	x			x	x
Anderlini et al., 1975	COE	13	x	x	x	x		x			
Baumgartner et al., 1987 unpubl.	EPA	10							x	x	x
Frizzell & Davies, 1986	RWQCB	19								x	
Peterson et al., 1972	USGS	206			x	x					
McCulloch et al., 1971	USGS	202	x								
USN, 1971	USN	9	x	x	x	x					x
Lui et al., 1975	COE	9	x	x	x	x					
Serne & Mercer, 1975	COE	8	x	x	x	x	x			x	x
US Navy,1987	Navy	14	x	x	x	x		x		x	x
ESA, 1987	Navy	2	x	x	x	x		x		x	x
Stevenson et al., 1987	SBDA	4	x	x	x	x	x	x			

Table 2. Sources of biota contamination data from San Francisco Bay used in this report.

Authors	Sponsor	Sites Sampled	Biota	Hg	Cd	Cu	Pb	Cr	Ag	PAH	DDT	PCB
Shimmin and Tunzi,1974	EPA	16	oysters, clams	x	x	x	x	x			x	x
Anderlini et al., 1975a, b	COE	2 to 30	bivalves	x	x	x	x	x	x		x	x
Girvin et al., 1975	CRWQCB	3 to 7	clams,mussels	x	x	x	x	x	x		x	x
Risebrough et al., 1978	ABAG	27 to 29	mussels	x	x	x	x	x	x		x	x
CH2M-Hill, 1979	San Francisco	8	bivalves	x	x	x	x	x	x		x	x
McCleneghan et al., 1982	CWQCB	10	clams, mussels	x	x	x	x	x	x		x	x
Kinney and Smith, 1982	EBMUD	3	clams	x	x	x	x	x	x		x	x
Hayes et al., 1985; Hayes and Phillips, 1986, 1987	CFG/CWQCB	23 to 32	mussels	x	x	x	x	x	x	x	x	x
Boehm et al., 1987	NOAA	2 to 3	mussels	x	x	x	x	x	x	x	x	x
Farrington et al., 1982	EPA	9	mussels		x	x	x		x		x	x
Luoma et al., 1984, 1987	USGS		bivalves		x	x		x	x			
Bradford & Luoma, 1980	USGS	5	bivalves			x			x			
NOAA, 1987	NOAA	4	fish	x	x	x	x	x	x		x	x
Spies et al., 1985 a,b	NOAA	4 to 5	fish							x	x	x
Cain and Luoma, 1985	USGS	2	clams			x			x			
Foe and Knight, 1986	Dow Chem, EPA	5	clams			x						
Wyland, 1975	n/a	4	clams, mussels	x	x	x	x	x	x			
Graham, 1971	n/a	1	clams, mussels		x	x		x	x			
Butler and Schutzman, 1971	EPA	2	fish	x	x		x				x	x
Guard et al., 1983	CFG	1	crab							x		
Stevens, 1980	CFG	1	fish								x	x
Whipple, 1984	NOAA	6	fish							x	x	x
Butler, 1977	NOAA/EPA	3	fish								x	x
Haugen, 1983	CFG	1	crab								x	x
Stout and Beezhold, 1981	NOAA	1	fish								x	x
Stout, unpublished	NOAA	1	shrimp								x	x
Bailey et al., 1967	CDWR	5	fish								x	
Butler, 1973,	EPA		clams, mussels									
Butler et al., 1978a,b	EPA		clams, mussels								x	
Earnest and Benville, 1971	USFWS		fish								x	
Modin, 1969	US BCF	1	oysters, fish								x	
Risebrough et al., 1965	US BCF	1	fish								x	
Risebrough, 1969	n/a	1	fish								x	

3

GEOGRAPHIC AND TEMPORAL TRENDS IN MERCURY CONTAMINATION

A. Sediments

Data have been compiled by numerous investigators on the concentration of mercury in the surface sediments of San Francisco Bay and its environs for the years 1970 through 1987. Based on more than 1,000 samples collected throughout the system, the grand mean concentration of mercury in San Francisco Bay sediments for the last 18 years was 0.50 parts per million (ppm) with a standard deviation of 0.67 ppm and a range of from less than 0.01 to 6.8 ppm (Table 3). The vast majority of the mercury values (84 percent) was between 0.10 and 1.00 ppm inclusive; 9 percent were less than 0.10 ppm (more than a quarter of which were below detection limits), while 7 percent were greater than 1.00 ppm. The median value was 0.38 ppm.+

(1) Geographic Trends

The most thorough study of mercury contamination in San Francisco Bay was conducted by the USGS in 1970 (McCulloch, et al., 1971). The USGS analyzed 202 samples of the upper 6 inches of sediment from throughout the Bay area for mercury and other metals. They found an overall mean mercury concentration of 0.34 ppm with a standard deviation of 0.54 ppm and a range of from 0.02 to 6.43 ppm (Figure 3). The data from the 202 samples are merged for the major basins and peripheral areas and summarized in Table 4. When the USGS data were transformed to base 10 logarithms and subjected to ANOVA followed by Scheffés F-test,* they indicated that mean mercury concentrations in the sediments of the basins of Suisun Bay, central, and south bays were significantly lower than the combined mean concentration of the peripheral areas of the south Bay (p=0.05). The mean concentration of mercury in the San Pablo Bay basin was significantly lower than that of the south Bay periphery (p=0.10). As determined by an unpaired one-tailed T-test, the peripheral areas of San Francisco Bay, overall, had a significantly higher mean concentration of mercury than the basins, overall (p=0.01). The sample with the highest concentration of mercury was taken from Islais Creek (6.43 ppm).

From 1971 through 1979, numerous dredging studies were conducted in the harbors and channels of San Francisco Bay under the auspices of the COE (COE unpublished sheets, 1975-1979; 1979b). The number of areas sampled and the specific areas sampled varied from year to year, with a maximum of 15 areas sampled in 1971 to a minimum of 4 areas sampled in 1977 and 1979. In addition, the sampling depth varied among samples, ranging from the upper 6 inches to the upper 5 feet with the most frequent sampling depth being the upper 2.5 feet. The areas most consistently sampled were Mare Island Strait, Richmond Harbor Channel, Oakland Inner and Outer Harbors, and Alameda Naval Air Station. The yearly means ranged from a low of 0.16 ppm (in 1976) to a high of 0.74 ppm (in 1974) with five of the nine values falling between 0.4 ppm and 0.5 ppm (Figure 3). The high yearly mean was in 1974 and it was strongly influenced by samples from two areas: Oakland Inner Harbor and off the mouth of Islais Creek. Four of these samples were taken between Grove Street Pier and Brooklyn Basin in the Oakland Inner Harbor and had mercury concentrations ranging from 2.42 ppm to 4.90 ppm, representing four of the five highest mercury values measured during the 9-year period. Eight of the samples were taken off the mouth of Islais Creek and included the fourth and sixth highest mercury concentrations for the 9-year period. If the data from these two areas were excluded, the mean concentration for 1974 would have been 0.53 ppm.

+ Unless otherwise stated, all concentrations are in dry weight, shown as ppm.

* Unless otherwise stated, all statistical analysis was carried out on the data after they were transformed to base 10 logarithms and consisted of ANOVA followed by Scheffés F-test.

There were no significant differences among areas sampled in 3 of the 9 years (1972, 1978, 1979) (p=0.05) as shown in Table 5. With one exception (1974), in those years where a significant difference did apppear (1971, and 1973 through 1977), the difference was only between the areas with the maximum values and the ones with the minimum values. In 1974, Oakland Inner Harbor had the highest mean mercury concentration in its sediments (3.41 ppm). This value was significantly higher than all others except the second highest mean value (1.26 ppm), found off the mouth of Islais Creek. The ranking of sites varied from year to year with no clear patterns appearing (Table 5); however, whenever either Pinole Shoals or the Carquinez Strait/Suisun Bay basin were sampled (three times each), they always had either the lowest or next to lowest mean mercury concentrations and the concentrations were always significantly different from the areas with the highest concentrations. Since Pinole Shoals and Carquinez Strait/Suisun Bay are considered as basin areas in this report, these results lend support to the conclusion based on the USGS data that the basins had slightly lower mean levels of mercury in the sediments than the peripheral areas. The COE dredging data further indicate that there were no significant differences among mean mercury concentrations in the sediments of various harbor (peripheral) areas of San Francisco Bay.

In 1972, the United States Navy conducted a dredging study (U.S.Navy, 1972) at the Hunters Point Naval Shipyard. Based on nine samples, the mean mercury concentration in the upper 6 inches of sediment was 0.62 ppm (Figure 3) with a standard deviation of 0.17. Figure 4 illustrates the mean mercury concentrations at the areas sampled in 1972 by the COE and the Navy.

In 1973 and 1974, several intensive studies were sponsored by the COE to determine the environmental impact of dredging and dredge spoil disposal. The Pollution Distribution Study (COE, 1979b) analyzed 48 samples from three areas of San Francisco Bay in 1973: eastern San Pablo Bay and Carquinez Strait, including Mare Island Strait; San Pablo Strait/Berkeley Flats; and Oakland Inner and Outer Harbors. The overall mean concentration of mercury in the upper 6 inches of sediment was 0.93 ppm with a standard deviation of 0.74 ppm and a range from 0.10 to 3.9 ppm (Figure 3). The highest single value (3.9 ppm) was recorded for a site east of Treasure Island, and the lowest value (0.1 ppm) was recorded for sites at Pinole Shoals and Oakland Inner Harbor. When the data from the 48 individual sites were pooled into 10 subareas (smaller than those designated by the COE) and examined, the highest mean mercury concentration was for five sites in the Berkeley Flats (1.30 ppm) followed by Pinole Shoals (18 sites, 1.20 ppm) and San Pablo Strait (six sites, 1.0 ppm). The lowest mean concentration was found in Oakland Inner Harbor (five sites, 0.36 ppm). While these results indicate a pattern in which basin areas had higher mercury concentrations than peripheral areas, there were no significant differences among the 10 sampling subareas (p=0.05).

In December 1973 and again in March and June 1974, Lui et al. (1975) analyzed sediment samples taken with a modified Petersen grab from seven sites around the Bay, as part of the COE's intensive dredging study. The site means for mercury contamination of the sediments, based on the three sampling periods, ranged from a low of 0.07 ppm at the Alcatraz Disposal Site to a high of 0.38 ppm at the South Bay Disposal Site. The second lowest mean mercury concentration was 0.21 ppm at the entrance to Redwood City Harbor. The only site which was significantly different than any of the other sites was the Alcatraz Disposal Site. During the December sampling period, it had the lowest mean concentration of mercury and was significantly different from four of the six other sites (p=0.05). All the concentrations determined in this study were lower than the grand mean for the Bay (Figure 3).

As part of the COE's intensive dredge study, Serne and Mercer (1975) analyzed a total of 33 sediment samples from eight areas for mercury concentrations during August 1973 and June 1974. The means ranged from a low of 0.39 ppm at Southampton Shoal to a high of 1.49 ppm at Islais Creek Shoals. Statistical analysis of the data indicated no significant differences between areas sampled (p=0.05).

Anderlini et al. (1975a) analyzed sediment samples from 13 sites in Mare Island Strait five times from October through December, 1973. In addition, they analyzed sediment samples from six of the sites four times from February through April 1974. The overall mean level of mercury found in the sediments was 0.47 ppm with a standard deviation of 0.11 ppm and a range from 0.27 to 0.80 ppm. Ten of the sites were paired down the length of the strait, two were paired off the southern tip of Mare Island, and the thirteenth site was located at the disposal site off the southern end of Mare Island. When the mean mercury concentrations were calculated for each pair of sites, they ranged from 0.53 ppm, for the pair of sites farthest up the strait to 0.34 ppm at the mouth of the strait with each pair of sites having a lower mean than the pair immediately landward of it. There was no significant difference between adjacent pairs of sites, but the pair at the mouth of the strait was significantly different than the upper three pairs of sites (p=0.05). The pair of sites around the southern tip of Mare Island (mean of 0.41 ppm) were significantly different than the upper most pair of sites (p=0.10). The highest mean mercury concentration (0.58 ppm) was found at the disposal site.

CH2M-Hill prepared a report in 1979 for the City and County of San Francisco on the effects of untreated sewage overflows on the eastern portion of south San Francisco Bay (CH2M-Hill, 1979). Sediments from the upper 10 to 13 cm at 23 sites between China Basin and Brisbane Lagoon were analyzed for mercury. Multiple samples (two to five) were collected at each site. The overall mean concentration of mercury at the 23 sites was 0.66 ppm with the means of the individual sites ranging from less than 0.12 to 2.50 ppm (Figure 3). The highest mercury concentration (2.50 ppm) was found at the head of the China Basin channel and decreased at each site from the head to the mouth of the channel. This same pattern of decreasing mercury concentrations from the head to the mouth of a channel was also observed in Islais Creek, where the site at the head of the channel had a mean mercury concentration of 1.20 ppm, while the site at the mouth had a mean of 0.34 ppm.

The SBDA conducted a 5-year monitoring program from 1982 through 1986 at four sites in the southern end of south Bay (Stevenson et al., 1987). They sampled the upper 5 cm of the sediments. Two of the sites were located in the basin of the south Bay, one slightly north of Dumbarton Bridge, and the other about midway between the bridge and the mouth of Coyote Creek. The other two sites were located in peripheral areas of the Bay, one in Coyote Creek and the other in Guadalupe Slough. The overall mean concentration of mercury in the sediments at the four study sites over the 5-year period was 1.35 ppm. The overall means for the individual sites for the same period ranged from 1.17 to 1.50 ppm. However, there were extremely high mercury values (3.2-6.8 ppm) during 3 of the 19 sampling periods (July and October 1983; January 1984). If the data from these sampling periods had been excluded from the calculations, then the overall mean would have been 0.65 ppm and the individual site means would range from 0.60 to 0.71 ppm. The overall means for these studies exceeded the grand mean for the Bay in 1982, 1983, and 1984, but were similar to the grand mean in 1985 and 1986 (Figure 3). The only significant difference between sites occurred in 1982 when the two south Bay sites were significantly different from each other; the site north of the Dumbarton Bridge had a mean of 1.33 ppm, while the site south of the bridge had a mean of 1.80 ppm.

In 1986, a study on the potential environmental impact of homeporting the *U.S.S. Missouri* in San Francisco Bay was carried out for the U.S. Navy (U.S. Navy, 1987), followed by a supplemental study in 1987 (ESA, 1987). In 1986, sediment core samples were taken from four sites around the piers of Hunters Point Naval Shipyard and six sites around Treasure and Yerba Buena islands. The upper 12 inches of the cores were analyzed for mercury. Two more sites at Hunters Point were sampled and analyzed in 1987. The mean mercury concentration at the 12 sites was 0.41 ppm with a range of from 0.20 to 0.66 ppm. When the data were log-transformed and subjected to an unpaired T-test, there was no significant difference between the Hunters Point sites and the Treasure Island and Yerba Buena Island sites (p=0.05).

In 1984, the Benthic Surveillance Project (BS) of NOAA's NS&T Program began analyzing samples of the upper 3 cm of sediment for heavy metal concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (NOAA, 1987a). Samples from the same sites, with the exception of the site off Oakland, were again analyzed in 1985. The overall mean mercury concentration for the 2-year period was 0.22 ppm with a range of from less than the detection limit of 0.014 ppm to 2.17 ppm. The site means ranged from 0.06 ppm at the Southampton Shoal site to 0.35 ppm at the site off Oakland (Figure 5). Both the highest single sample value and all the below detection limit values were determined in samples collected in 1984. Eight of the twelve samples taken in 1984, including two from the San Pablo Bay site, had mercury levels below detection. The 2.17 ppm value was recorded for the third sample from the San Pablo Bay site in 1984. In both 1984 and 1985, samples from a site in Bodega Bay, an area minimally influenced by anthropogenic activities, were also analyzed for heavy metal concentrations. The 2-year mean for the site was 0.14 ppm, with a range of from below the detection limit to 0.21 ppm. In 1985, the San Pablo Bay site (0.03 ppm mercury) was significantly different than the other two sites in the Bay (0.11 and 0.35 ppm mercury) and the Bodega Bay site (0.14 ppm mercury) (p=0.05). There were no other statistically significant differences among sites for each of the 2 years or for the 2-year period combined (p=0.05).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) survey at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Chapman et al., 1986). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean mercury concentration in the sediments, based on three samples per site, was 0.40 ppm with a range of 0.09 to 1.20 ppm (Figure 3). The San Pablo Bay site (with a mean of 0.21 ppm) was significantly different than the Islais Creek site (with a mean of 0.71 ppm) (p=0.05).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for heavy metal concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba Buena Island, and near the San Mateo Bridge. In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987). The analyses were carried out on the upper 1 cm of sediment. The overall mean mercury concentration for the sites in the Bay, based on three samples per site, was 0.28 ppm with a range of 0.06 to 0.42 ppm (Figure 3). The individual site means ranged from 0.13 ppm at Semple Point to 0.34 ppm at Point San Pedro; the Tomales Bay mean was 0.30 ppm (Figure 5). Semple Point was significantly different than the other four sites, while there were no significant differences among any of the other sites (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 0.29 ppm, and statistical analysis indicated no significant difference between sites (p=0.05) including the Semple Point site. Figure 5 displays the mean concentrations from the NS&T Program data for the sites sampled in 1984 through 1986.

(2) Temporal Trends

No broad-scale, long-term monitoring of mercury concentrations has been conducted in the Bay. Rather, data have been collected in various parts of the Bay in many separate studies. During the 18-year period for which data have been compiled, mercury concentrations in the sediments of the Bay have fluctuated from year to year, but have displayed no long-term trends. Figure 3 contains a comparison of the means by study and year to the grand mean. Despite these yearly fluctuations, no long-term trend of increasing or decreasing concentrations of mercury throughout the Bay are apparent. Because of the high variability in mercury concentrations from sample to sample, the yearly fluctuations may be simply due to within-site patchiness and the selection of individual stations where samples were taken each year. Some studies were performed in peripheral areas and others were conducted mainly in the basins of the Bay.

The COE has performed analyses of prospective dredge material in five peripheral areas for 7 to 9 years. The data were not collected to determine temporal trends. Rather, they were collected to assess contamination in various project areas. Therefore, samples were not taken at the same sites each year. Figure 6 indicates that mean concentrations for the same five harbor areas that were sampled repeatedly fluctuated yearly over a 9-year period, but with no apparent long-term trends (COE unpublished data sheets, 1975-79; 1979b). The high degree of variability from year to year at these sites may be partially due to variations in the sample size (from 1 to 26) and within-site patchiness encountered in sampling each year. Concentrations of mercury at all of these sites were relatively low in 1976.

The other data set, which extended over several years at the same sites, was from the SBDA studies in the southern end of the south Bay. From April 1982 through April 1986, the SBDA sampled two sites located in the south Bay basin and two sites in peripheral areas on a quarterly basis. The mean mercury concentrations in the surficial sediments were between 1.00 and 2.00 ppm at the beginning of the study period, decreased to 0.41 ppm then rose sharply in July 1983, reaching a maximum of 5.40 ppm in October 1983 (Figure 7). The mean remained high in January 1984, then dropped off sharply in April 1984, remaining between 0.37 and 0.60 ppm for the remainder of the study.

When the yearly mean mercury concentrations of the NOAA NS&T Program data from all the sites were compared for 1984 through 1986, there were no significant differences between years (p=0.05). The means for the 3 years were, 0.31 ppm in 1984 and 0.28 ppm in 1985 and 1986.

B. Biota

Mercury concentrations have been measured in fish and bivalves in 12 surveys since 1973. Pooling all data (311 samples) on mercury concentrations in mussels (*Mytilus edulis, M. californianus*) analyzed from 1973 through 1986 shows the overall mean mercury concentration for San Francisco Bay to be 0.4 ppm (Table 6). Mercury levels in bivalves have ranged from 0.09 to 3.22 ppm. The data indicate that mercury is distributed at similar levels in the three basins for which there are substantial data. However, since each basin is unevenly represented in the calculation of these means, the results must be interpreted with caution. Specifically, south Bay has been sampled frequently, whereas only one data point was found for the Suisun Bay/Carquinez Strait basin. Mercury levels in San Francisco Bay mussels are elevated above those from reference areas (Tomales Bay and Bodega Head) by a factor of approximately 2. Mean concentrations and ranges for mussels sampled in the Bay are illustrated for each study and compared to the grand mean for the Bay in Figure 8.

(1) Geographic Trends

The analysis of mercury in Japanese littleneck clams (*Tapes semidecussata*) or soft-shell clams (*Mya arenaria*) by the US EPA in 1972 (Shimmin and Tunzi, 1974) showed clams from Point Richmond and Tara Hills to be the most contaminated. These clams contained 0.09 ppm ww mercury (approximately 0.8 ppm). Clams from sites in the south Bay contained lower mercury concentrations than those taken from central Bay or San Pablo Bay sites.

The sampling of Bay mussels (*Mytilus edulis*) in 1975 (Girvin et al., 1975) showed that highest concentrations of mercury were found at Redwood Creek (3.22 ppm) (Figure 8). Mussels from Coyote Point and Islais Creek also contained elevated mercury levels (0.84 and 0.71 ppm, respectively). Peripheral areas produced mussels with higher levels of mercury than most basin sites. Clams (*Tapes japonica*) sampled during 1975 by the same survey showed highest levels of mercury at Foster City (1.21 ppm). Clams (*Tapes japonica*) from Redwood Creek also contained elevated mercury levels (0.90 ppm). Lowest concentrations (0.28 ppm) of mercury were found in clams from Bayview Park near San Mateo.

In 1980, the sampling of bay mussels (*Mytilus edulis*) from 12 sites in the Bay showed highest levels of mercury to be detected at Coyote Point (0.42 ppm) (Hayes et al., 1985; McCleneghan et al., 1982). Mussels from Point Isabel, Redwood Creek, and Dumbarton Bridge contained approximately 0.30 ppm mercury. Mussels from peripheral areas (near Point Isabel and the Bayshore Lagoon) contained lower mercury levels than those from some basin sites. Mussels sampled from sites in the south Bay contained higher levels of mercury than those from central Bay or San Pablo Bay. Mussels sampled by McCleneghan et al. (1982) showed no significant differences in mercury concentrations among sites (p=0.05). Sampling of Japanese littleneck clams (*Tapes japonica*) in 1980 by McCleneghan et al. (1982) and Kinney and Smith (1982) showed highest mercury levels at Foster City (1.36 ppm). Clams from near 3rd Avenue (San Mateo) contained 0.70 ppm mercury. As with bay mussels, clams from south Bay sites contained higher concentrations of mercury than those taken from central Bay or San Pablo Bay (Figure 9). The clams sampled by Kinney and Smith (1982) showed no difference in mercury levels between sites (p=0.05). However, those sampled by McCleneghan et al. (1982), showed mercury levels at Foster City to be significantly different than those at four other sites (Point Isabel, Anza Lagoon, Burlingame, and Point Richmond; p=0.05).

The NS&T Program (NOAA, 1987a) analyzed mercury in the livers of starry flounder (*Platichthys stellatus*) or white croaker (*Genyonemus lineatus*) from four sites in San Francisco Bay and a site in Bodega Bay in 1984 (Figure 10). These analyses showed highest concentrations of mercury in liver tissue of starry flounder taken from Southampton Shoal (5.83 ppm). Lowest mercury levels were found in liver tissue of starry flounder from San Pablo Bay (less than 0.08 ppm). Statistical analyses of the data indicated that levels at Southhampton Shoal were significantly different than those at San Pablo Bay (p=0.05). The sites and fish species sampled by the NS&T Program have apparently not been surveyed by other investigators.

In 1985 and 1986, the California State Mussel Watch Program (Hayes and Phillips, 1986; 1987) analyzed mercury in coastal mussels (*Mytilus californianus*) transplanted to 10 sites in San Francisco Bay, and in resident mussels (*M. californianus*) from Bodega Head (Figure 11). Highest levels of mercury were found in mussels transplanted to Dumbarton Bridge (0.52 ppm) and to parts of the Oakland Inner Harbor (approximately 0.45 ppm). Mussels transplanted to sites in the south Bay had mercury levels higher than those transplanted to central Bay or San Pablo Bay sites.

In 1986, the NOAA NS&T Program (Boehm et al., 1987) analyzed mercury in resident mussels (*M. edulis*) from the San Mateo Bridge, Dumbarton Bridge, Tomales Bay, and Bodega Head (Figure 11). Concentrations of mercury in mussels were similar from all sites (approximately 0.27 ppm) except from Bodega Head, where mercury levels (0.12 ppm) were significantly lower (p=0.05). Results of sampling by the NS&T Program are generally comparable to results generated by other surveys that sampled mussels nearby. At the San Mateo Bridge, other investigators (Hayes et al., 1985; Hayes and Phillips, 1986; Risebrough, et al., 1978) detected a mean of 0.38 ppm, while the NS&T Program detected 0.27 ppm. At the Dumbarton Bridge, the same investigators detected 0.43 ppm between 1976 and 1985, while the NS&T Program detected 0.28 ppm at a nearby site. At Bodega Head, Hayes et al. (1985) and Hayes and Phillips (1986) detected 0.25 ppm in mussels between 1976 and 1986, while the NS&T Program found 0.12 ppm in mussels sampled nearby. In Tomales Bay, other surveys (Hayes et al., 1985; Hayes and Phillips, 1986; Anderlini et al., 1975 a, b; Wyland, 1975) detected an average of 0.23 ppm, as compared to 0.28 ppm detected in mussels by the NS&T Program.

(2) Temporal Trends

Resident bay mussels (*M. edulis*) have been resampled at three sites since 1975. Sampling at Foster City, or nearby on the San Mateo Bridge, indicated mercury concentrations have remained at approximately 0.30 ppm (Girvin et al., 1975; Hayes et al., 1985; Boehm et al., 1987). Sampling at Redwood Creek (and at two sites nearby) indicate a decline in mercury levels since 1975 (from 3.2 to 0.31 ppm). Concentrations of mercury in mussels from the Dumbarton Bridge have remained near 0.30 ppm since 1980.

Clams (*Tapes spp.*) have been resampled in two areas of San Francisco Bay since 1972 (Shimmin and Tunzi, 1974; Girvin et al., 1975; McCleneghan et al., 1982; Kinney and Smith, 1982). Sampling at Foster City indicates that mercury levels may have increased in Japanese littleneck or soft-shell clams since 1972 (from approximately 0.26 to 1.36 ppm by 1980). Samples taken from Albany Hill or nearby at Point Isabel show clams to have contained approximately 0.30 ppm mercury since 1972.

Transplanted mussels (*M. californianus*) have been resampled at eight sites in San Francisco Bay since 1979 (Hayes and Phillips, 1986, 1987). No changes in mercury levels were apparent from these analyses (Figure 12). However, mercury levels declined slightly in early 1982 at six of the eight sites where transplanted mussels were resampled. Mercury concentrations in resident mussels from Bodega Head have varied from 0.09 to 0.45 ppm with no significant changes between years (p=0.05).

C. Summary

Mercury concentrations in the sediments of San Francisco Bay and its environs display a small scale patchiness and a large scale homogeneity. This pattern is illustrated in Figure 3 where mercury concentrations for individual samples ranged from 0.01 to 6.80 ppm (a 680-fold difference), but mean concentrations for each study ranged from 0.15 to 2.85 ppm (a 19-fold difference). The mean concentrations for the studies only exceeded 1 ppm in three instances, all in SBDA investigations. Also, COE surveys alternately ranked the Oakland Inner Harbor as relatively highly contaminated, then least contaminated among the areas tested in two studies. These differences may have been due to variability within that area.

The means, standard deviations, medians, and ranges of mercury concentrations in sediments in the four basins and selected peripheral areas, based on data from all the studies compiled for this report, are listed in Table 7. It also includes the number of samples taken at each area and the years in which sampling took place. While the table orders the areas from highest to lowest means, any comparisons of areas must be done with extreme caution because of differences in sampling and analytical methodologies, time of sampling, and number of samples taken at each area. There were no differences in concentrations among basins and among peripheral areas. Possibly the most significant statistics in Table 7 are the ranges that show a high degree of overlap for all the areas sampled, both basins and peripheral areas. The means and medians are highest for four peripheral areas--Coyote Creek, China Basin, Islais Creek, and Guadalupe Slough--but the standard deviations are very high and the ranges in values overlap those from two basins--central Bay, Carquinez Strait/Suisun Bay--with the lowest mean concentrations. The grand mean for the Bay (0.50 ppm, Table 3) exceeds the mean concentrations for two reference sites, Bodega Bay (0.14 ppm) and Tomales Bay (0.30 ppm) by factors of 3.6 and 1.7 times, respectively.

While the overall data indicate that mercury concentrations in the sediments of San Francisco Bay display a small-scale patchiness and a large-scale homogeneity, the data from the individual studies indicate a pattern in which the basins of the Bay have slightly lower concentrations of mercury than the peripheral areas. The existence of this pattern is supported by the USGS study in 1970 where the basin mean was 0.23 ppm and the peripheral mean was 0.59 ppm. The COE dredging studies from 1971 through 1979 indicated a generally lower mean mercury concentration in those basin areas sampled. While the 1973 Pollution Distribution Study appears to show the basin areas with higher mean mercury concentrations than the peripheral areas, there was no significant difference between any of the areas sampled. Additional support comes from Anderlini's 1973 study of Mare Island Strait (Anderlini et al., 1975a) that showed a decreasing trend in mercury concentrations moving down the Strait, and CH^2M Hill's 1979 study that showed the same pattern of decreasing mercury concentrations moving down China Basin and Islais Creek.

Most of the mercury data available for biota in the Bay are from mussels, both residents and transplants. The mean concentrations in areas in San Francisco Bay are relatively similar, rarely exceeding a two-fold difference in mean concentrations among sites and in comparison with mussels from Tomales Bay and Bodega Head. There are no apparent large trends among basins of the Bay; the means, medians, and ranges are similar (Table 6). However, there is a pattern, though inconsistent, of relatively higher mercury concentrations in some samples from the southern portion of the south Bay area compared to the central Bay sampling areas. Highest single concentrations in mussels have been observed in samples from Berkeley Marina, Alameda Yacht Harbor, and Redwood Creek sites. The highest single concentration exceeds the grand mean for mussels in the Bay by a factor of 8. The grand mean concentration (0.40 ppm) exceeds the means for Tomales Bay and Bodega Head by a factor of approximately 2.

The determination of broad-scale trends in mercury contamination in other biota is precluded by small data sets for individual species. However, some of the data from analyses of clams appear to indicate elevated concentrations in the Redwood Creek and Foster City areas of south Bay. Samples of fish at Southhampton Shoal have had relatively high mercury concentrations compared to fish from other sites in the Bay.

The available data indicated yearly as well as quarterly fluctuations in mercury concentrations in sediments, but no long-term trend was apparent. COE dredging studies at five harbors from 1971 through 1979 showed this yearly fluctuation (Figure 6) and indicated that 1976 had exceptionally low mercury concentrations. The 1976 low was possibly due to low river flows and runoff as a result of the drought that California experienced at that time. Quarterly fluctuations were apparent in the SBDA study where mean mercury concentrations underwent over a 10-fold increase from one quarterly sampling period to another and then displayed an equally sharp decrease two quarters later.

As with the sediment data, the biota data show year-to-year variations in mercury concentrations at sampling sites and areas, but no significant trends of increasing or decreasing concentrations. While the lowest mean concentration in sediments was observed in 1976, 1982 had the lowest observed mean concentrations in mussels.

Historical mean concentrations of mercury in sediments sampled from 1972 through 1986 in San Francisco Bay are compared in Figure 13 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper case print. The NS&T Program sites are in lower-case print. Those from the 1984 Benthic Surveillance Project are designated by "BS" after the site name; those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold type. The overall historical mean for the Bay (0.50 ppm) was relatively high compared to the 1986 Pacific Coast sites. South Bay and peripheral areas, especially Coyote Creek, were particularly contaminated. Suisun Bay had relatively low levels. Among the 1984 Benthic Surveillance and 1986 Mussel Watch Project sites along the Pacific Ccast, the eastern San Pablo Bay site ranked fourth, the Oakland site ranked seventh, and Hunters Point and Southhampton Shoal ranked among the lowest in mercury concentrations. Both of the reference sites, Tomales Bay and Bodega Bay, ranked low in mercury concentration in sediments.

The historical mean concentrations of mercury in mussels collected in San Francisco Bay from 1972 through 1986 are compared in Figure 14 with means from three samples of mussels each from NS&T Program Pacific Coast sites sampled in 1986. The historical areas are designated in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located within the Bay are listed in bold print. In these comparisons, the calculated historical values from the Bay include data from peripheral hot spots that may no longer exist. The data from the NS&T Program are largely from coastal and estuarine sites not immediately affected by point sources. Only resident mussels are sampled at the NS&T Program sites, whereas both residents and transplants were sampled by others in the Bay. The grand mean for San Francisco Bay and the means for its major basins were relatively high compared to the Pacific Coast sites. These means were only equalled or exceeded by those from the Oceanside Beach jetty in southern California and the Barber's Point boat basin in Hawaii (the samples in Hawaii are of the oyster, *Ostrea sandwichensis*). The Redwood Creek area was highly contaminated relative to other parts of the Bay and the NS&T Program 1986 samples. Among the 1986 NS&T Program Pacific Coast sites, the San Mateo Bridge and Dumbarton Bridge sites in the south Bay were ranked seventh and sixth, respectively, in mercury concentration. The two reference sites, Tomales Bay and Bodega Head, were ranked third and twenty-third, respectively.

Table 3. Bay-wide means, standard deviations, medians, and ranges of mercury concentrations in surficial sediments of San Francisco Bay based on data collected by many investigators from 1970 through 1987 from the four basins and peripheral harbors and waterways (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	0.50	0.67	0.38	<0.01-6.80	1097
BASINS	0.45	0.73	0.26	<0.01-6.60	396
PERIPHERY	0.52	0.63	0.40	0.01-6.80	701

Table 4. Means, standard deviations, medians, and ranges of mercury concentrations in surficial sediments of San Francisco Bay for 1970, based on U. S. Geological Survey data (McCulloch et al., 1971) (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
BASINS					
CARQUINEZ STR/SUISUN BAY	0.25	0.30	0.11	0.02-1.25	35
SAN PABLO BAY	0.28	0.29	0.20	0.04-1.20	24
CENTRAL BAY	0.18	0.14	0.13	0.04-0.75	41
SOUTH BAY	0.24	0.20	0.17	0.04-1.00	43
BASIN TOTAL	0.23	0.23	0.15	0.02-1.25	143
PERIPHERY					
CARQUINEZ STR/SUISUN BAY	0.47	0.55	0.21	0.08-2.00	14
SAN PABLO BAY	0.41	0.23	0.42	0.06-0.65	6
SOUTH BAY	0.66	1.02	0.40	0.13-6.43	39
PERIPHERY TOTAL	0.59	0.88	0.41	0.06-6.43	59

Table 5. Yearly ranking of areas, from highest to lowest mercury levels, sampled by the COE from 1971 through 1979, based on the ANOVA and Scheffé's F-test of the log-transformed data (bars connect those areas that are not significantly different at p=0.05) .

1971*	1972	1973
ISLAIS CRK OAKLAND INNER HBR RICHMOND HBR SAUSALITO CHNNL PETALUMA RVR SAN BRUNO CHNNL OAKLAND OUTER HBR PINOLE SHOALS SUISUN BAY	PETALUMA CHNNL ALAMEDA NAS RICHMOND HBR PT MOLATE REDWOOD CITY HBR COYOTE PT MRN MARE ISLAND STR SAN LEANDRO MRN OAKLAND OUTER HBR PT DAVIS	ALAMEDA NAS PETALUMA CHNNL PETALUMA RVR OAKLAND INNER HBR NORTH CENTRAL BAY PINOLE SHOALS CARQUINEZ STR
1974	**1975**	**1976**
OAKLAND INNER HBR ISLAIS CREEK RICHMOND HBR OAKLAND OUTER HBR RICHMOND HBR CHNNL ALAMEDA NAS PT MOLATE MARE ISLAND STR	OAKLAND OUTER HBR MARE ISLAND STR OAKLAND INNER HBR RICHMOND HBR CHNNL PINOLE SHOALS	PETALUMA CHNNL BERKELEY BRKWTR RICHMOND HBR CHNNL MARE ISLAND STR ALAMEDA NAS OAKLAND INNER HBR OAKLAND OUTER HBR SUISUN BAY**
1977	**1978**	**1979**
MARE ISLAND STR OAKLAND OUTER HBR OAKLAND INNER HBR RICHMOND HBR CHNNL	OAKLAND INNER HBR MARE ISLAND STR OAKLAND OUTER HBR RICHMOND HBR CHNNL ALAMEDA NAS	OAKLAND INNER HBR OAKLAND OUTER HBR MARE ISLAND STR RICHMOND HBR CHNNL

* Those areas with less than three samples were excluded from the analysis (Mare Island Strait, Alameda NAS, Point Molate, Redwood City Harbor, Sonoma Creek, and Napa River).

** In 1976, Suisun Bay was only significantly different from Petaluma Channel; however, all three samples from Suisun Bay were below the detection limit of 0.1 ppm, therefore half the detection limit was used in the analysis.

Table 6. Means, medians, and ranges in concentration of mercury in mussels (*Mytilus edulis* or *Mytilus californianus*) collected by many investigators during 1973-1986, in basins and peripheral areas of San Francisco Bay (ppm dw).

AREA/SITE		MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY						
	BASIN	0.27	-	-	-	1
SAN PABLO BAY						
	BASIN	0.38	0.16	0.35	0.16-0.74	33
	PERIPHERAL-MARE ISL. ST.	0.35	0.01	0.31	0.23-0.49	25
CENTRAL BAY						
	BASIN	0.31	0.08	0.30	0.09-0.73	105
	PERIPHERAL-RICHMOND HBR.	0.29	0.09	0.28	0.21-0.38	4
	PT. ISABEL	0.19	0.00	-	0.19-.019	2
	BERKELEY MARINA	0.82	0.47	0.79	0.29-1.89	12
	ALL PERIPHERAL	0.63	0.47	0.51	0.19-1.9	18
SOUTH BAY						
	BASIN	0.41	0.13	0.37	0.19-0.91	85
	PERIPHERAL-ISLAIS CREEK	0.71	-	-	-	1
	BELMONT SLOUGH	0.33	-	-	-	1
	ALAMEDA YACHT HBR.	0.82	0.76	-	0.28-1.35	2
	OAKLAND INNER HARBOR	0.33	0.14	0.36	0.14-0.45	4
	OAKLAND OUTER HARBOR	0.16	-	-	-	1
	BAYSHORE LAGOON	0.23	0.09	-	0.17-0.29	2
	PALO ALTO YACHT HBR.	0.38	-	-	-	1
	REDWOOD CREEK	0.59	0.52	0.51	0.3-3.22	30
	ALL PERIPHERAL	0.54	0.48	0.43	0.14-3.22	42
ALL S.F. BAY		0.40	0.25	0.33	0.09-3.22	311
TOMALES BAY		0.23	0.08	0.23	0.12-0.41	22
BODEGA HEAD		0.21	0.10	0.18	0.09-0.45	22

Table 7. Means, standard deviations, medians, and ranges of mercury concentrations in the surficial sediments of San Francisco Bay for the four basins, selected peripheral areas, and the NOAA NS&T Program reference sites based on data collected by many investigators from 1970 through 1987 (ppm dw). The Bay sites are ordered from highest to lowest mean.

AREA	YEARS SAMPLED	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
COYOTE CREEK	82-86	1.50	1.97	0.56	0.37 - 6.80	19
CHINA BASIN	79	1.33	1.08	1.22	0.36 - 2.50	4
ISLAIS CREEK	70, 71, 74, 79, 85	1.30	1.40	0.88	0.20 - 6.43	20
GUADALUPE SLOUGH	82-86	1.17	1.37	0.51	0.26 - 5.40	19
SOUTH BAY	70, 71, 73, 74, 79, 82-86	0.65	1.13	0.33	<0.01 - 6.60	114
0AKLAND INNER HBR	71, 73-79	0.57	0.79	0.36	0.02 - 4.90	75
HUNTERS POINT NS	72-74, 86, 87	0.53	0.18	0.50	0.28 - 0.89	17
SAN PABLO BAY	70-73, 75, 76, 84-86	0.45	0.53	0.30	<0.01 - 2.80	112
PT MOLATE	71, 72, 74	0.44	0.16	0.42	0.20 - 0.90	17
MARE ISLAND STR	70-79	0.43	0.22	0.42	0.02 - 1.30	199
OAKLAND OUTER HBR	71-79	0.42	0.26	0.40	0.01 - 1.10	66
REDWOOD CITY HBR	71-74	0.42	0.21	0.40	0.03 - 0.80	16
ALAMEDA NAS	71-74, 76, 78	0.41	0.30	0.41	0.05 - 1.30	60
RICHMOND HARBOR	71-79	0.40	0.28	0.40	0.02 - 1.94	112
CENTRAL BAY	71, 71, 73, 74, 76, 84-86	0.35	0.44	0.26	<0.01 - 3.90	111
CARQUINEZ STR./SUISUN BAY	70, 71, 73, 74, 76	0.23	0.26	0.11	0.02 - 1.25	57
TOMALES BAY	86	0.30	0.03	0.31	0.27 - 0.32	3
BODEGA BAY	84, 85	0.14	0.08	0.15	<0.01 - 0.21	6

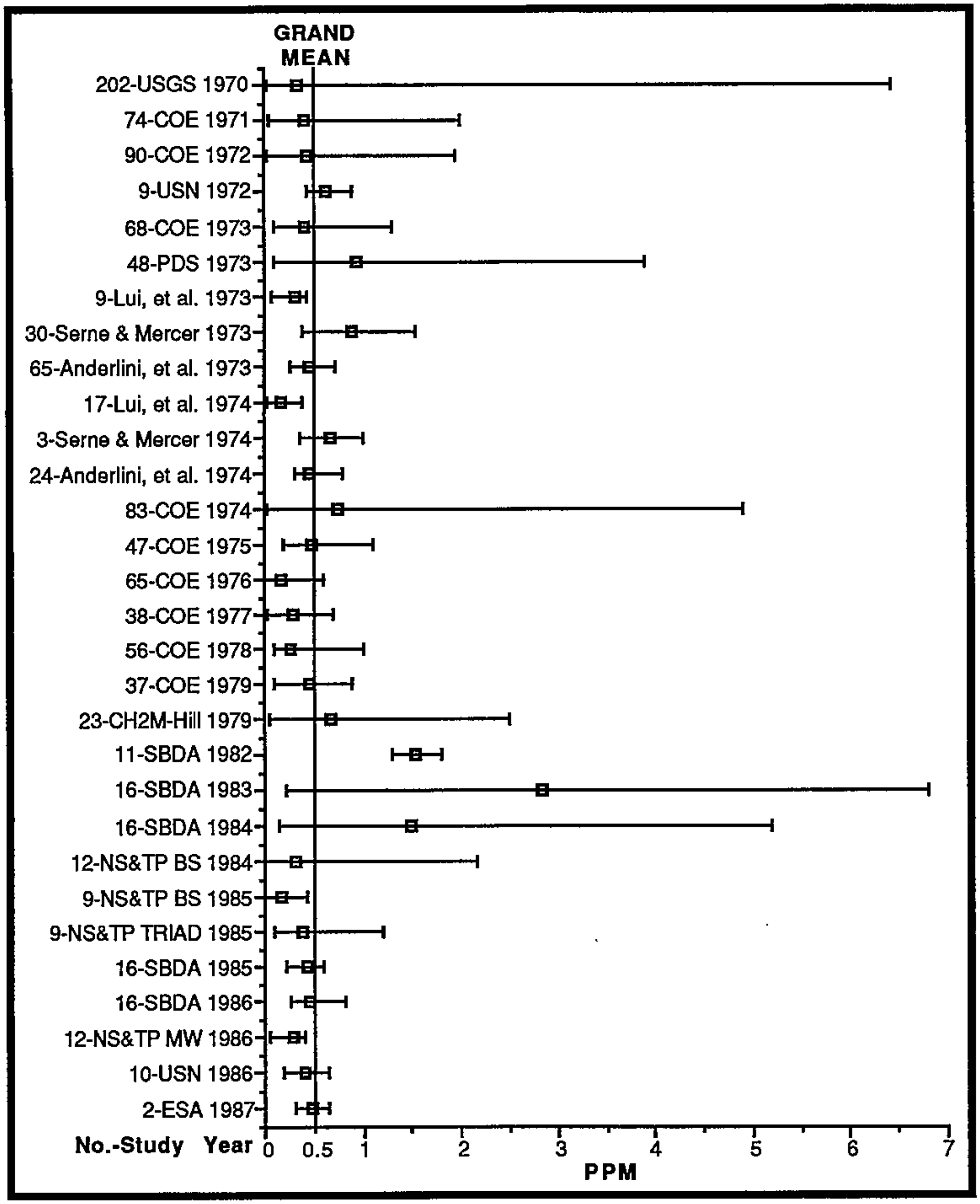


Figure 3. Mean concentration of mercury in the surficial sediments of San Francisco Bay by study and year compared to the grand mean for the Bay (ppm dw) (No.=number of samples, bars represent the range).

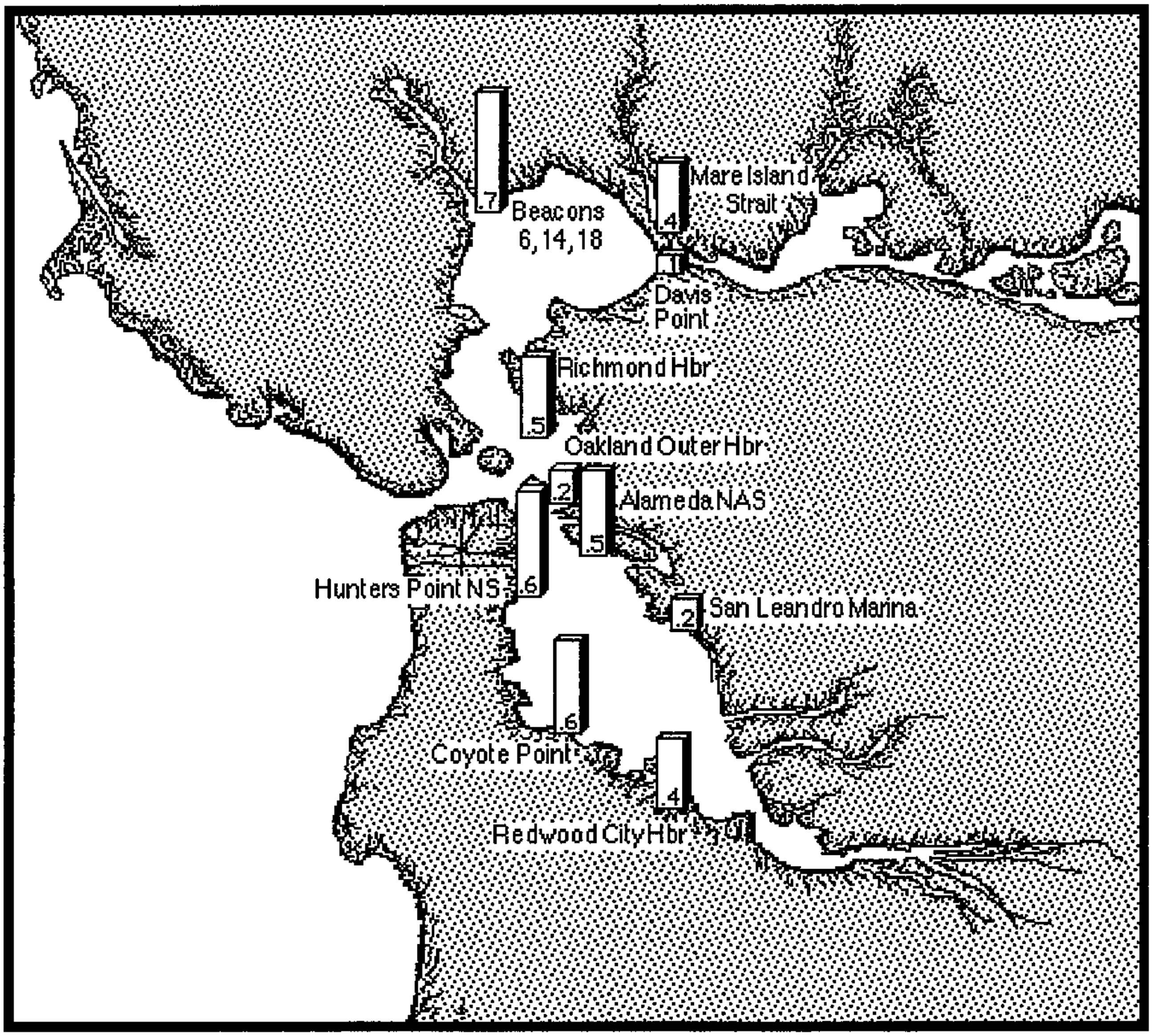


Figure 4. Mean mercury concentrations in the sediments (ppm dw) based on 1972 dredging studies (COE, 1979a; U.S. Navy, 1972).

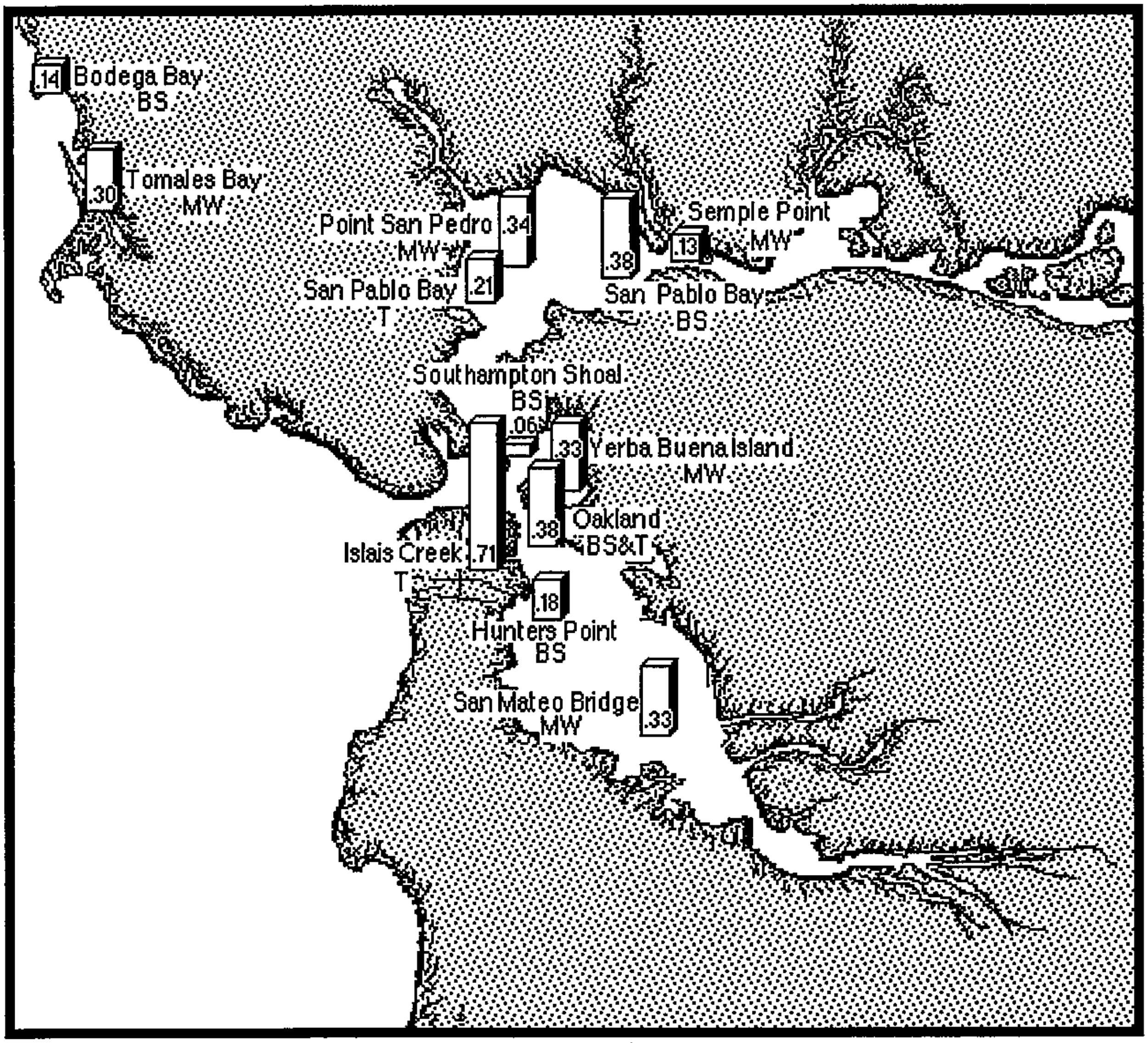


Figure 5. Mean mercury concentrations in the surficial sediments for 1984-86, in ppm dw, based on NOAA NS&T Program data (BS=Benthic Surveillance, MW=Mussel Watch, and T=Sediment Quality Triad Study) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986).

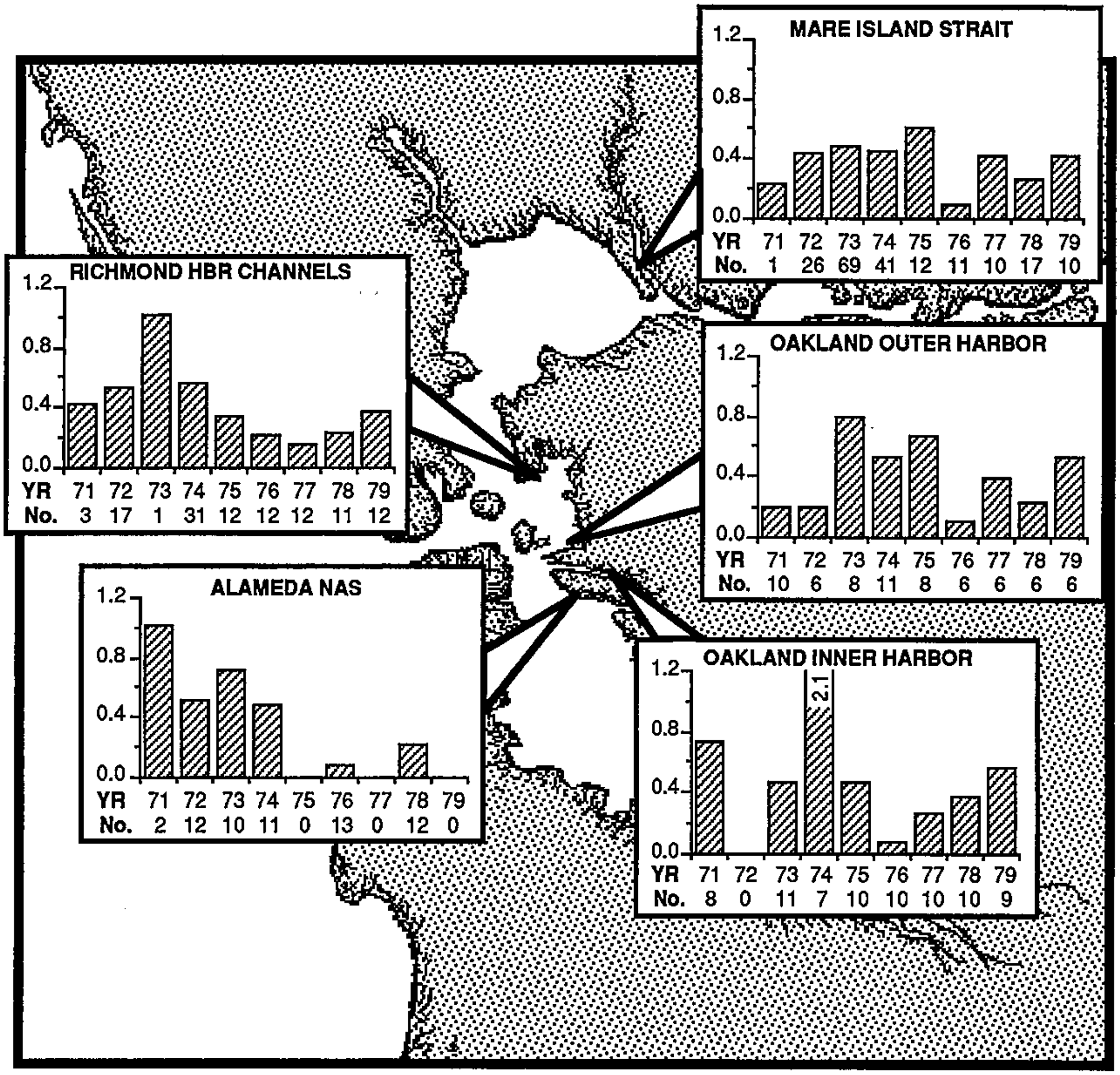


Figure 6. Mean mercury concentrations (ppm dw) at five sites from 1971 to 1979, based on dredging studies (COE, unpublished data sheets1975-79, 1979b).

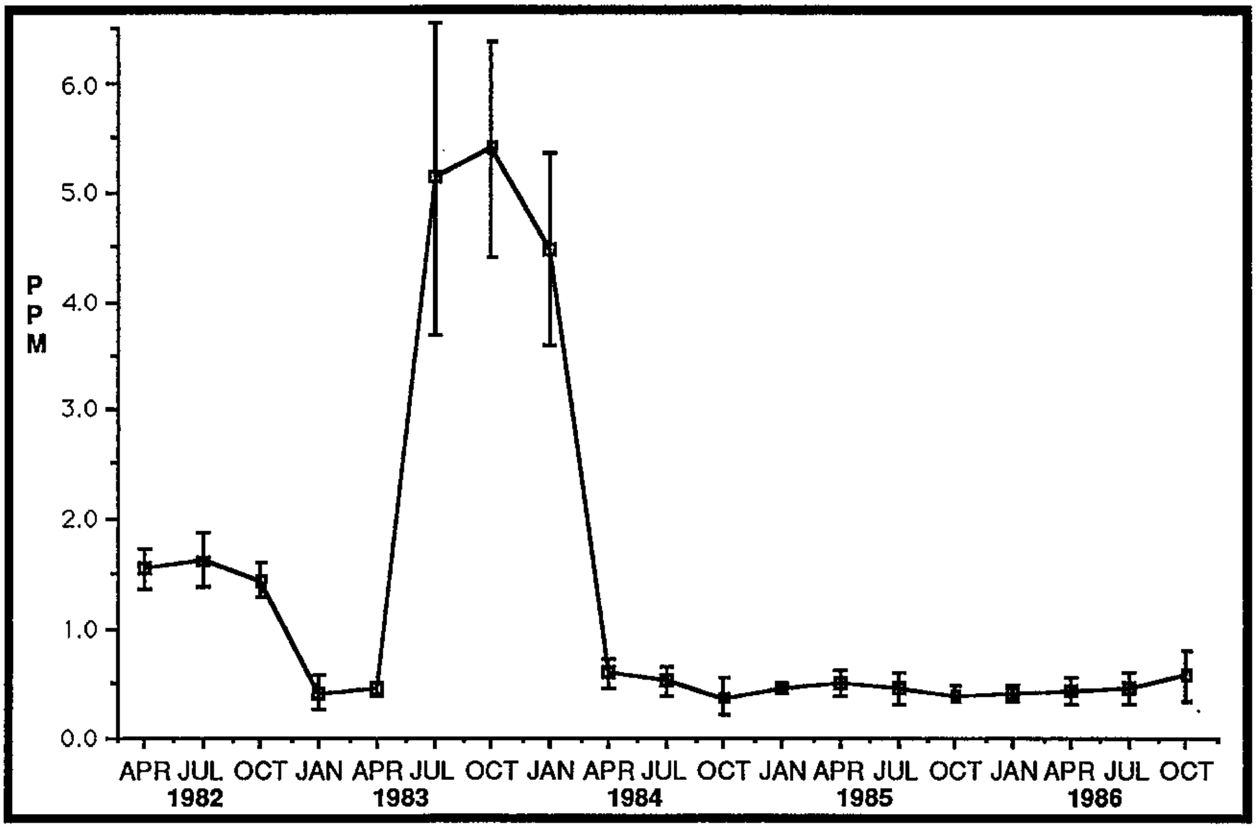


Figure 7. Monthly mean mercury concentration in the surficial sediments at the four sites in the southern end of south Bay sampled by the SBDA from 1982 through 1986 (bars represent one standard deviation) (Stevenson et al., 1987).

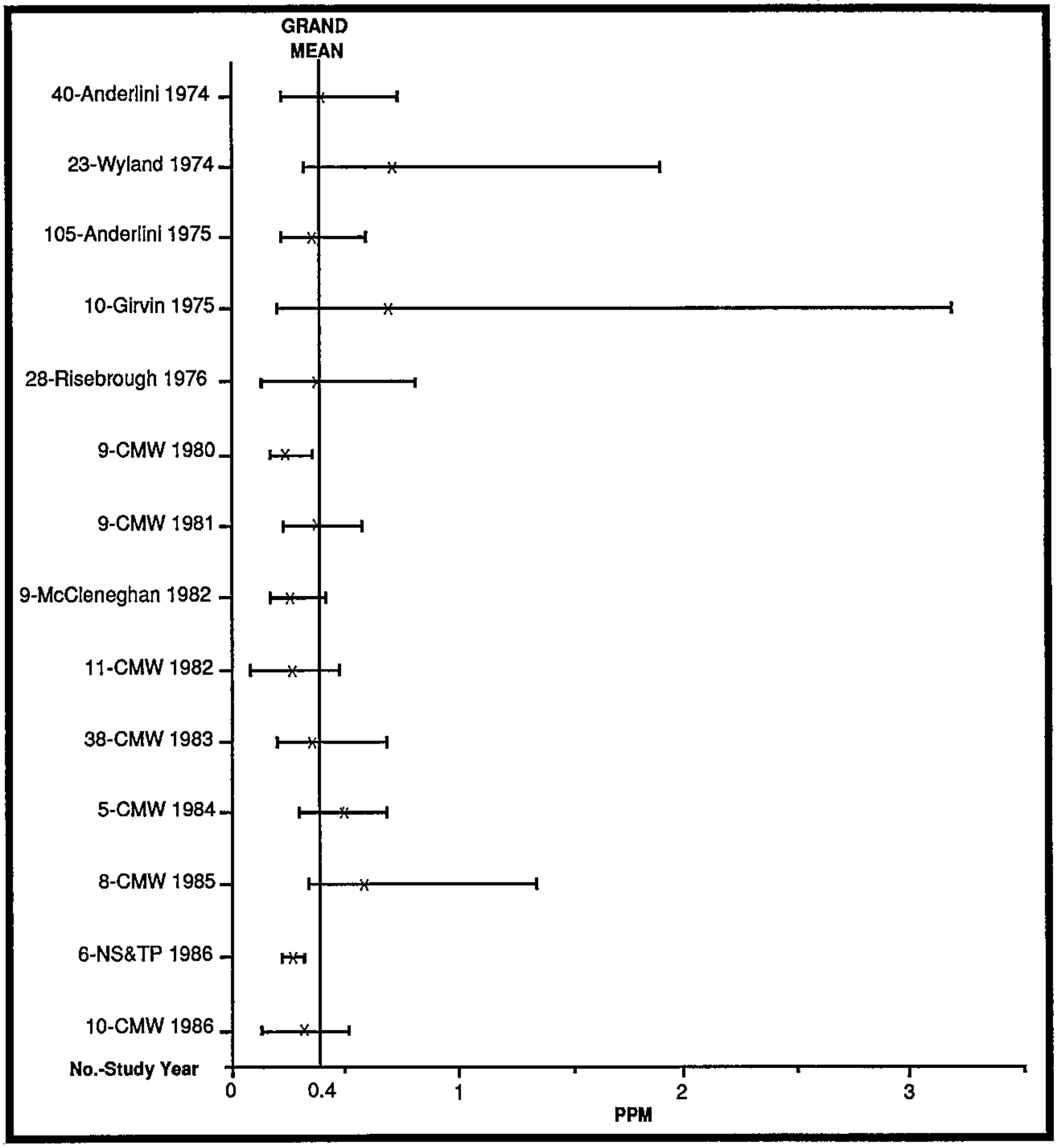


Figure 8. Mean concentration of mercury in mussels (Mytilus edulis or Mytilus californianus) by study and year in ppm dw (No.=number of samples, bars represent the range).

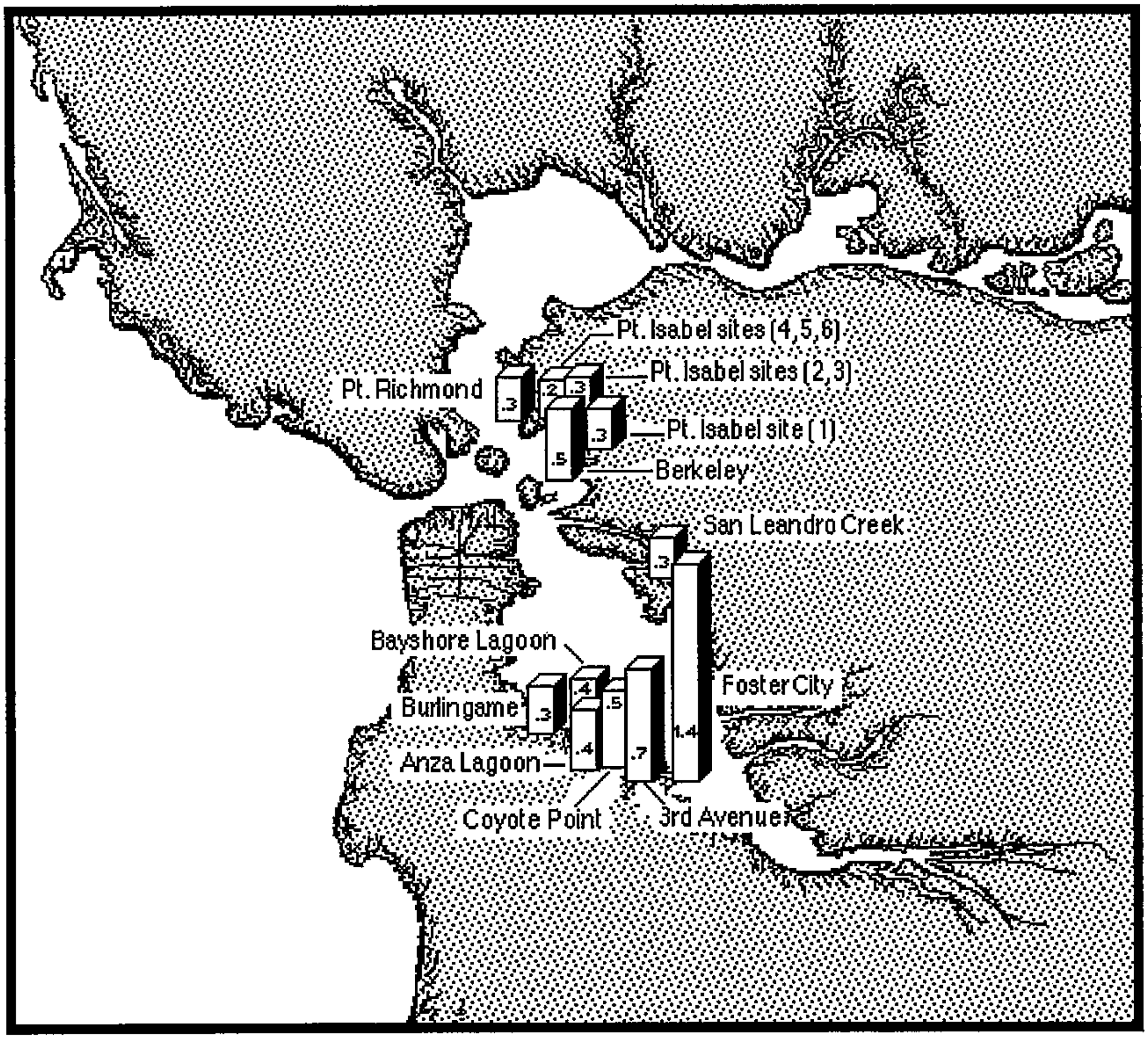


Figure 9. Concentration of mercury in Japanese littleneck clams (Tapes japonica) in 1980 (ppm dw) (from McCleneghan et al., 1982; Kinney and Smith, 1982).

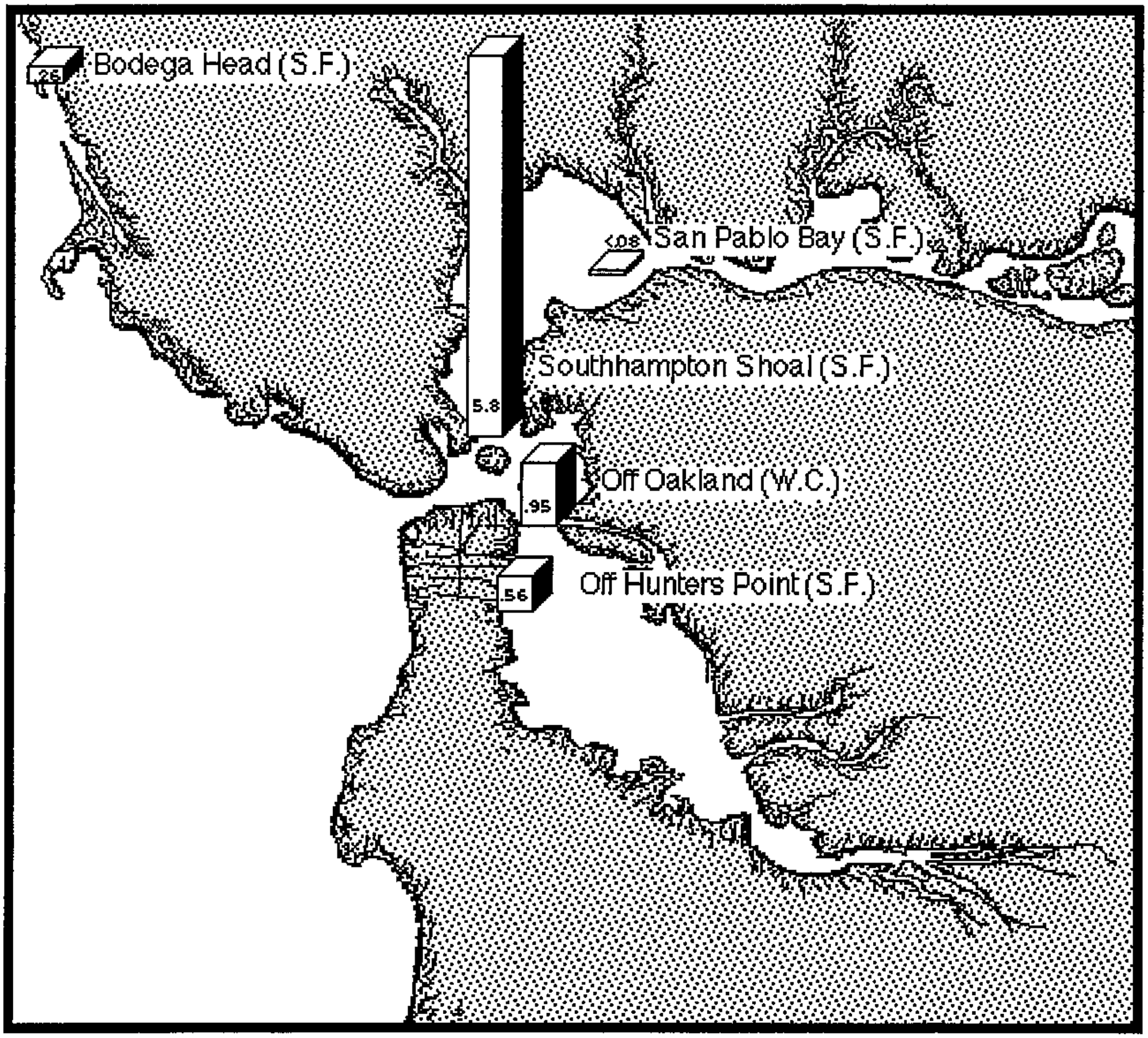


Figure 10. Mercury in liver tissue of starry flounder (S.F.), Platichthys stellatus, and white croaker (W.C.), Genyonemus lineatus, sampled in 1984 (ppm dw)(NOAA 1987a).

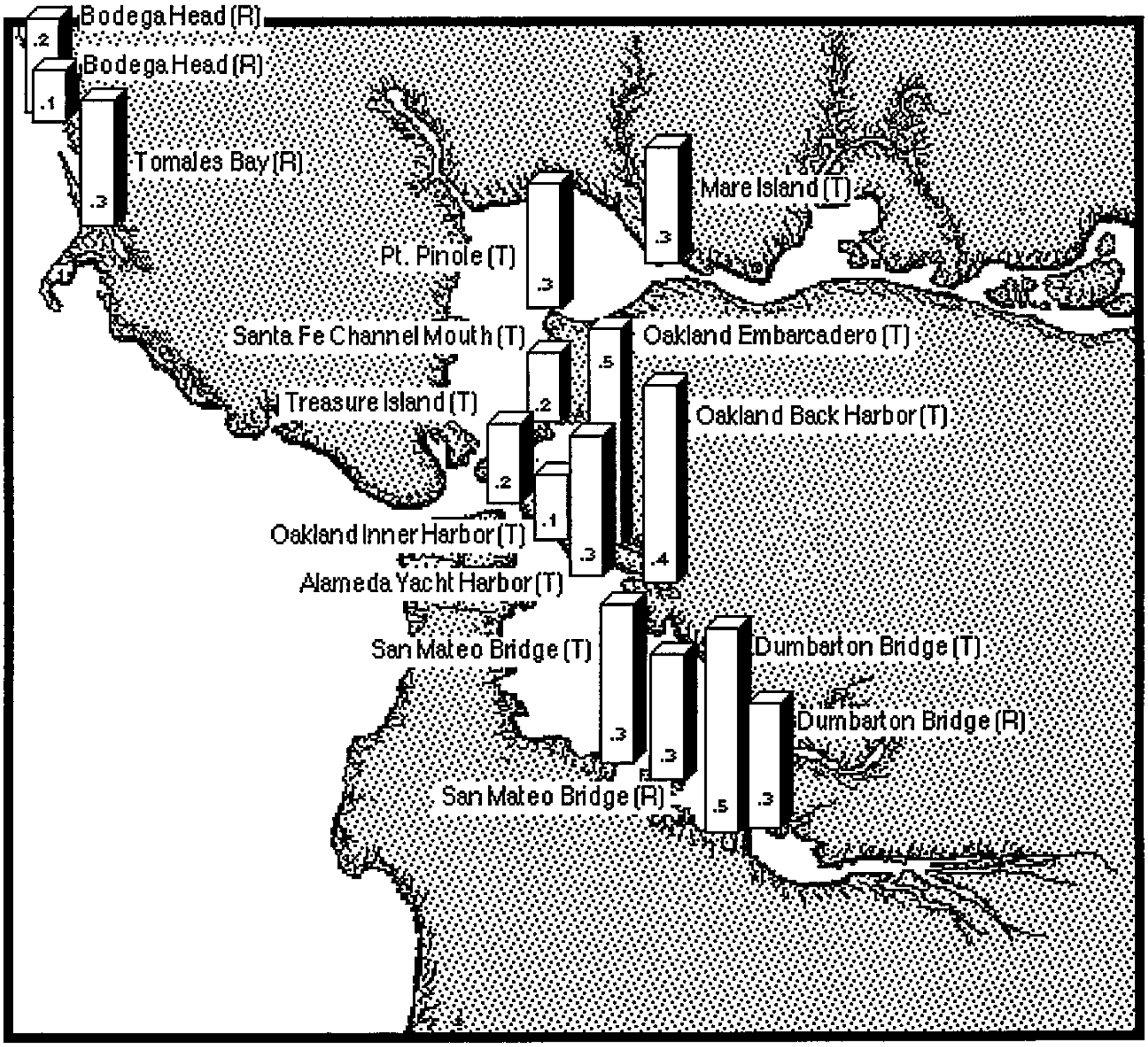


Figure 11. Mercury in transplanted (T) coastal mussels (Mytilus californianus) and resident(R) Bay mussels (M. edulis) in 1985-86 (ppm, dw)(from Hayes and Phillips, 1987; Boehm et al., 1987).

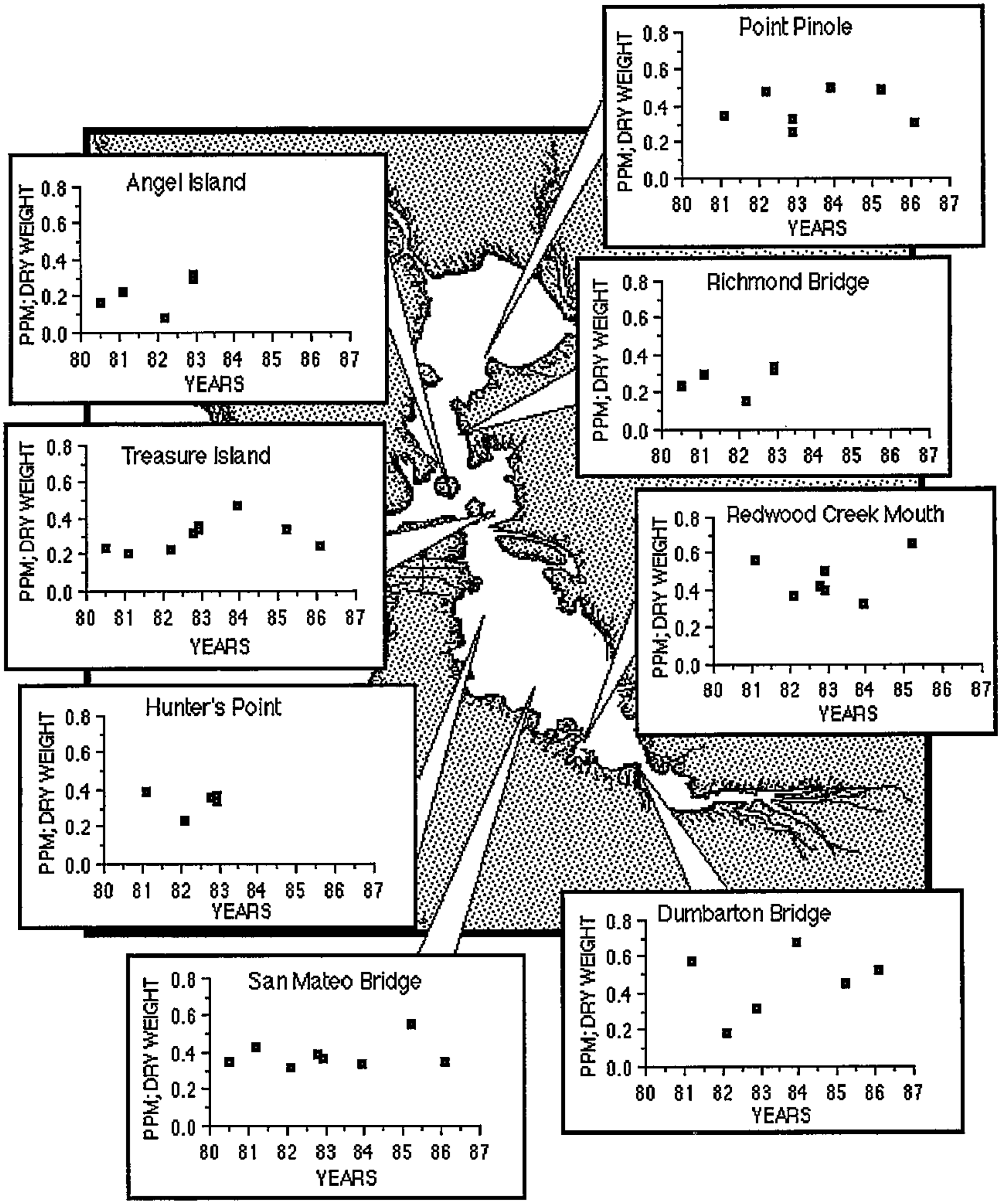


Figure 12. Temporal trends in mercury concentrations in transplanted mussels (Mytilus californianus), 1980-1986 (Hayes et al., 1985; Hayes and Phillips, 1986, 1987).

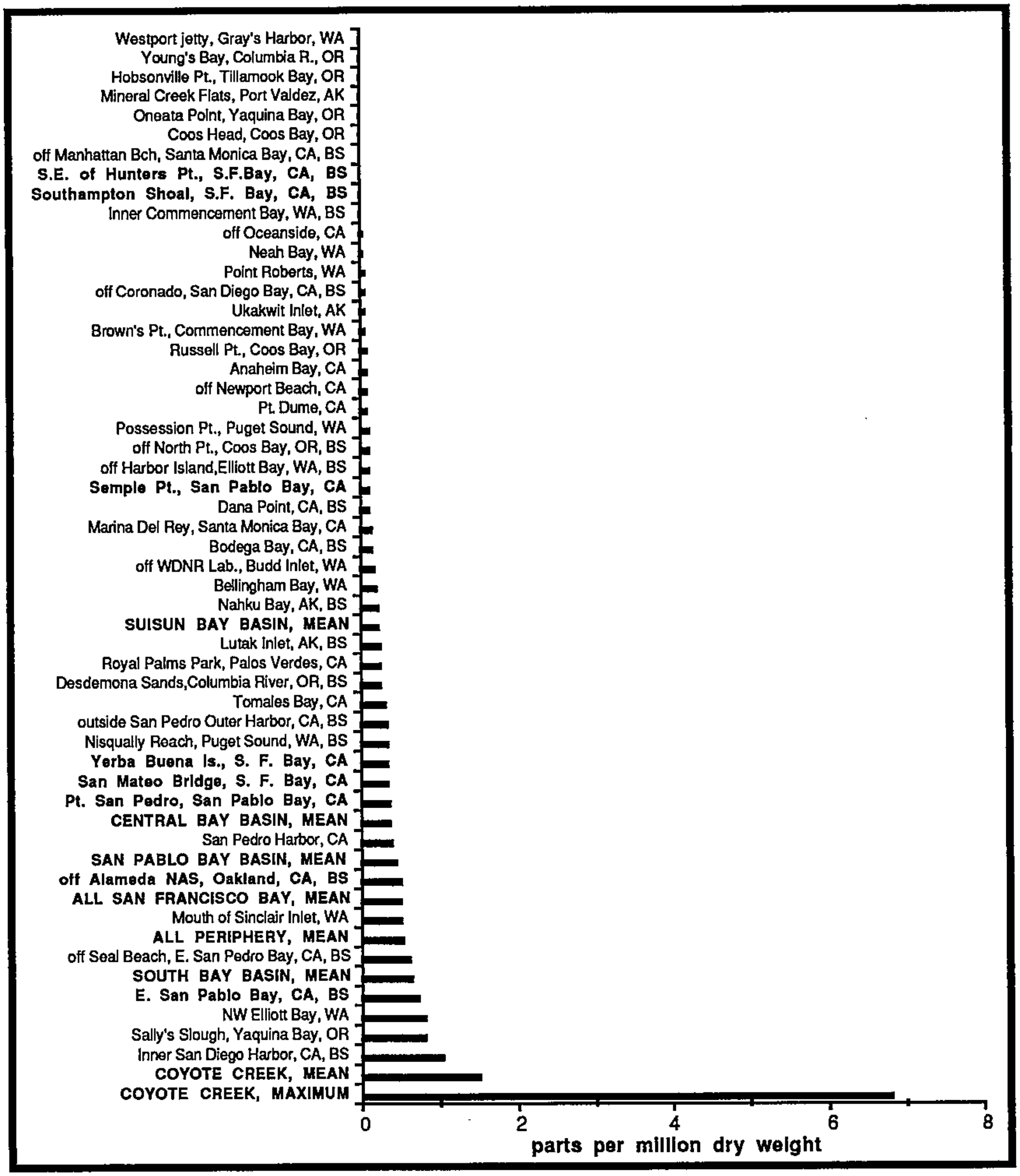


Figure 13. Comparison of mercury concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Tables 3, 7), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name).

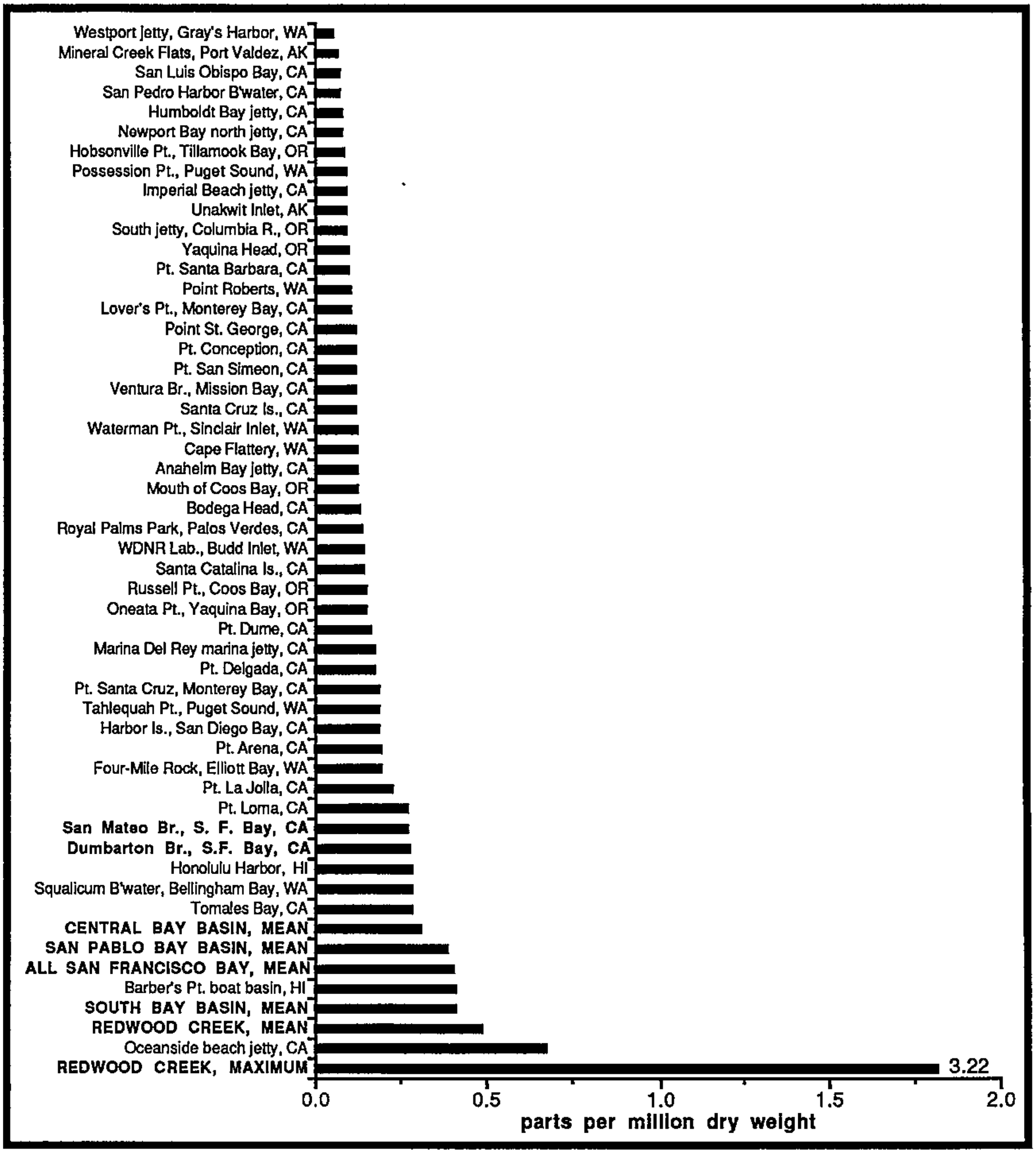


Figure 14. Mean mercury concentrations in resident mussels (Mytilus edulis, M. californianus) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1972-1986) data for San Francisco Bay (from Table 6). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

4

GEOGRAPHIC AND TEMPORAL TRENDS IN CADMIUM CONTAMINATION

A. Sediments

Data have been compiled by numerous investigators on the concentration of cadmium in the surface sediments of San Francisco Bay and its environs for the years 1971 through 1987. Based on 999 samples collected throughout the system, the mean concentration of cadmium in San Francisco Bay sediments for the last 17 years was 1.06 ppm with a standard deviation of 1.16 ppm and a range from 0.02 to 17.3 ppm (Table 8). The majority of the cadmium values (63 percent) were between 0.10 and 1.00 ppm inclusive; 2 percent were less than 0.10 ppm, while 34 percent were greater than 1.00 ppm. The median value was 0.71 ppm.

(1) Geographic Trends

From 1971 through 1979, numerous dredging studies were conducted in the harbors and channels of San Francisco Bay under the auspices of the United States COE (COE, unpublished data sheets 1975-1979; 1979b). The number of areas sampled and the specific areas sampled varied from year to year, with a maximum of eight areas sampled for cadmium in 1974 and 1976 and a minimum of four areas sampled in 1977 and 1979. In addition, the sampling depth varied from sample to sample, ranging from the upper 6 inches to the upper 5 feet with the most frequent sampling depth being the upper 2.5 feet. The areas most consistently sampled were Mare Island Strait, Richmond Harbor Channels, Oakland Inner and Outer Harbors, and Alameda NAS. The yearly means ranged from a low of 0.27 ppm to a high of 2.02 ppm with six of the nine values being less than 1.00 ppm (Figure 15). The highest yearly mean was in 1972 and it was strongly influenced by samples taken from Mare Island Strait, which included the single sample with the highest cadmium concentration (8.3 ppm) for all the COE dredging studies and third highest for all the data available for this report. Of the 26 samples analyzed from Mare Island Strait, 12 contained more than 2.00 ppm cadmium and the mean fo. the strait was 2.90 ppm.

There were no significant differences among areas sampled in 2 of the 9 years (1973 and 1979) ($p=0.05$) as shown in Table 9. While there was a significant difference between various sites during the other 7 years, the sites that were significantly different varied from year to year with no consistent pattern apparent. The ranking of sites also varied from year to year with no clear patterns appearing (Table 9). In 1975, Mare Island Strait had the highest mean concentration of cadmium (1.03 ppm) and was significantly different than Oakland Outer Harbor which had the lowest concentration of cadmium (0.26 ppm) for that year. In 1977, Oakland Outer Harbor had the highest concentration of cadmium (0.38 ppm) and was found to be significantly different than Mare Island Strait which had the lowest mean concentration of cadmium (0.25 ppm) for that year. In 1972, 1978, and 1979, there was no significant difference between Mare Island Strait and Oakland Outer Harbor. Based on the COE dredging data, there is no consistent pattern or geographic trend in cadmium contamination among those peripheral parts of San Francisco Bay that were studied.

In 1972, the United States Navy conducted a dredging study (U.S. Navy, 1972) at the Hunters Point Naval Shipyard. Based on nine samples, the mean cadmium concentration in the upper 6 inches of sediment was 0.83 ppm (Figure 15) with a standard deviation of 0.12. Figure 16 graphically shows the mean cadmium concentrations at the areas sampled in 1972 by the COE and the Navy.

In 1973 and 1974 several intensive studies were sponsored by the COE to determine the environmental impact of dredging and dredge spoil disposal. The Pollution Distribution Study (COE, 1979b) analyzed 48 samples from three areas of San Francisco Bay in 1973: eastern San Pablo Bay and Carquinez Straits, including Mare Island Strait; San Pablo Strait/Berkeley Flats; and Oakland Inner and Outer Harbors. The overall mean concentration of cadmium in the upper 6 inches of sediment was 1.02 ppm with a standard deviation of 0.58 ppm and a range from 0.08 to 3.2 ppm (Figure 15). The highest single value (3.2 ppm) was recorded for a site in Oakland Inner Harbor; the lowest value (0.08 ppm) was recorded for a site at Pinole Shoals. When the data from individual sites were pooled into smaller sampling areas than those designated by the COE and examined, the highest mean cadmium concentration was for three sites west of Point Richmond (1.57 ppm). The lowest mean concentration was found in the Berkeley Flats area (five sites, 0.80 ppm). There were no significant differences among the 10 sampling areas (p=0.05).

In December 1973 and again in March and June 1974, Lui et al. (1975) analyzed 45 sediment samples, taken with a modified Petersen grab, from seven sites around the Bay as part of the COE's intensive dredging study. The site means for cadmium contamination of the sediments, based on the three sampling periods, ranged from a low of 0.96 ppm at the South Bay disposal site to a high of 1.87 ppm at the Oakland Inner Harbor site. There were no significant differences between any of the sites at any time during this study (p=0.05).

As part of the COE's intensive dredge study, Serne and Mercer (1975) analyzed a total of nine sediment samples from six areas for cadmium concentrations during August 1973 and June 1984. The means ranged from a low of 0.71 ppm at Mare Island Strait to a high of 1.60 ppm at Islais Creek Shoals. Statistical analysis of the data indicated no significant differences between areas sampled (p=0.05).

Anderlini et al. (1975a) analyzed 58 sediment samples from 13 sites in Mare Island Strait during five sampling periods from October through December 1973. In addition, they analyzed sediment samples from six of the sites on four separate occasions from February through April 1974. The overall mean level of cadmium found in the sediments was 1.97 ppm with a standard deviation of 0.95 ppm and a range from 0.50 to 4.30 ppm. Ten of the sites were paired down the length of the strait, two were paired off the southern tip of Mare Island, and the thirteenth site was located at the disposal site off the southern end of Mare Island. When the mean cadmium concentrations were calculated for each pair of sites they ranged from 1.38 ppm for the pair of sites at the mouth of the strait, to 2.25 ppm at the adjacent pair of sites. There was no pattern of increasing or decreasing concentrations between the most upstream sites and the sites located at the mouth of the strait. There was no significant difference between any of the pairs of sites (p=0.05).

CH^2M-Hill prepared a report in 1979 for the City and County of San Francisco on the effects of untreated sewage overflows on the eastern portion of south San Francisco Bay (CH^2M-Hill, 1979). Sediments from the upper 10 to 13 cm at 23 sites between China Basin and Brisbane Lagoon were analyzed for cadmium. The overall mean concentration of cadmium at the 23 sites was 3.37 ppm with the means of the individual sites ranging from 1.30 to 17.3 ppm (Figure 15). The highest cadmium concentration (17.3 ppm) was found at the site approximately half a mile due east of the north end of Brisbane Lagoon. Decreasing cadmium concentrations from the respective heads to the mouths of both Islais Creek and China Basin were observed. The site at the head of Islais Creek had a mean cadmium concentration of 6.5 ppm while the site at the mouth had a mean concentration of 1.4 ppm; in China Basin, the values were 8.6 and 2.1 ppm, respectively.

In 1981, CH^2M-Hill (1981) conducted a study for the Castro Cove refinery of Chevron USA. They collected a total of 94 sediment samples from 29 sites in three areas: Castro Creek and marsh, Gallinas Creek, and Corte Madera Creek. Sampling was conducted on a quarterly basis from March through December 1983. The upper 15 cm of sediment were analyzed for cadmium contamination. The overall mean cadmium concentration for the study was 0.52 ppm with a standard deviation of 0.46 and a range of from 0.03 to 2.8 ppm (Figure 15). The mean cadmium concentrations for the three areas were: 0.62 ppm for Castro Creek, 0.47 ppm for Gallinas Creek, and 0.38 ppm for Corte Madera Creek. Analysis indicated that Castro Creek was significantly different than the other two areas (p=0.10).

Luoma et al. (1984) collected and analyzed 31 samples of the oxidized layer of sediment from 10 sites in Suisun Bay. The overall mean cadmium concentration for the study was 0.22 ppm with a standard deviation of 0.14 ppm and a range from 0.03 to 0.63 ppm. The means for the individual sites ranged from 0.03 ppm at Roe Island (one sample) to 0.34 ppm at Chain Island (five samples). There were no significant differences between any of the sites sampled (p=0.05).

Spies, et al. (1985b) collected and analyzed sediment samples from four sites (western San Pablo Bay, west of Berkeley, west of Oakland, and off the western end of Alameda Island) in San Francisco Bay in 1984. At three of the four sites, cadmium concentrations were below the detection limit of 2.5 ppm; at the fourth site, off Alameda Island, the cadmium concentration was 3 ppm.

The SBDA conducted a 5-year monitoring program from 1982 through 1986 at four sites in the southern end of south Bay (Stevenson et al., 1987). Two of the sites were located in the basin of the south Bay, one slightly north of Dumbarton Bridge and the other about midway between the bridge and the mouth of Coyote Creek. The other two sites were located in peripheral areas of the Bay, one in Coyote Creek and the other in Guadalupe Slough. The overall mean concentration of cadmium in the upper 5 cm of the sediments at the four sites during the 5-year period was 1.63 ppm, with the overall means for the individual sites ranging from 1.45 to 1.94 ppm. However, there were very high cadmium values (3.2-6.8 ppm) during 3 of the 19 sampling periods (July and October 1983; January 1984). These 3 months were significantly different than most of the other months (p=0.05). If these sampling periods were excluded from the calculations, then the overall mean would become 1.24 ppm, and the individual site means would range from 0.60 to 0.71 ppm. The overall means for each year and many individual concentrations exceeded the grand mean for the Bay (Figure 15). There were no significant differences between any of the sites during the study (p=0.05).

A study of the potential environmental impact of homeporting the *U.S.S. Missouri* in San Francisco Bay was carried out for the U.S. Navy in 1986 (U.S. Navy, 1987), followed by a supplemental study in 1987 (ESA, 1987). In 1986, sediment core samples were taken from a few sites around the piers of Hunters Point Naval Shipyard and six sites around Treasure and Yerba Buena islands; the upper 12 inches of the cores were analyzed for cadmium. Two more sites at Hunters Point were sampled and analyzed in 1987. The mean cadmium concentration of the 12 sites was 0.97 ppm with a range from 0.60 to 1.00 ppm. When the data were log-transformed and subjected to an unpaired T-test, there were no significant differences between the Hunters Point sites and the Treasure Island and Yerba Buena Island sites (p=0.05).

In 1984, the Benthic Surveillance Project (BS) of NOAA's NS&T Program began analyzing samples of the upper 1 cm of sediment for heavy metal concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (NOAA, 1987a). Sediment samples from the same sites, with the exception of the site off Oakland, were analyzed again in 1985. The overall mean cadmium concentration for the 2-year period was 0.29 ppm with a range of from 0.02 ppm to 0.64 ppm. The site means ranged from 0.16 ppm at the site off Oakland, to 0.32 ppm at the San Pablo Bay site. In 1984 and 1985, samples from a site in Bodega Bay, an area minimally influenced by anthropo- genic activities, were also analyzed for heavy metal concentrations. The 2-year mean for the site was 0.23 ppm, with a range of from below the detection limit of 0.001 to 0.53 ppm. There were no statistically significant differences among sites during the 2-year period (p=0.05). However, in 1985 the San Pablo Bay (0.57 ppm cadmium) and the Hunters Point (0.49 ppm cadmium) sites were significantly different than the Bodega Bay site (0.27 ppm cadmium).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) survey at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Chapman et al., 1986). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean cadmium concentration in the sediments, based on three samples per site, was 0.56 ppm with a range of 0.50 to 1.00 ppm (Figure 15). Analysis of the data indicated that there were no significant differences between sites (p=0.05).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for heavy metal concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba Buena Island, and near the San Mateo Bridge. In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987). The analyses were carried out on samples of the upper 1 cm of sediment. The overall mean cadmium concentration in the Bay, based on three samples per site, was 0.33 ppm with a range of 0.22 to 0.53 ppm (Figure 15). The individual site means ranged from 0.24 ppm at Yerba Buena to 0.48 ppm at Semple Point; the Tomales Bay mean was 0.37 ppm. Semple Point was found to be significantly different than the other three sites in the Bay, but not significantly different than the Tomales Bay site (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 0.36 ppm, and statistical analysis indicated no significant differences between sites (p=0.05), including the Semple Point site. Figure 17 displays the NS&T Program data for 1984 through 1986.

(2) Temporal Trends

No broad-scale, long-term monitoring of cadmium has been conducted in the Bay. Rather, data have been collected in portions of the Bay in many separate studies. During the 17-year period for which data have been compiled, cadmium concentrations in the sediments of the Bay have fluctuated from year to year and study to study, but have displayed no long-term trends. Figure 15 compares the means by study and year to the grand mean for the Bay. Some studies were performed in peripheral areas and others were performed mainly in the basins of the Bay. Despite these yearly fluctuations, no long-term trend of increasing or decreasing concentrations of cadmium throughout the Bay are apparent. The ranges in concentrations observed in most of the studies included the grand mean for the Bay. Because of the high variability in mercury concentrations from sample to sample, the yearly fluctuations may be simply due to within-site patchiness and the selection of individual stations from which samples were taken each year.

Figure 18 suggests that mean cadmium concentrations for five harbor areas have declined over a 9-year period, but caution is advised in interpreting the data in this figure because of the high number of values that were below detection limits. Also, the high degree of variability from year to year at these sites may be partially due to variations in the sample size (from 1 to 26) and within-site patchiness encountered in sampling each year.

The only other data set, which extended over several years at the same sites, was the SBDA study in the southern end of the south Bay. From January 1982 through April 1986, the SBDA sampled two sites located in the south Bay basin and two sites in peripheral areas on a quarterly basis. The mean cadmium concentrations in the surficial sediments were between 0.65 and 1.65 ppm at the beginning of the study period, then rose sharply in July 1983, reached a high of 4.52 ppm in July 1983, dropped to 2.98 ppm in October 1983, and rose again to 3.85 ppm in January 1984. In April 1984, the mean concentration dropped to 0.71 ppm and remained between that value and 1.98 ppm for the remainder of the study (Figure 19).

When the yearly mean cadmium concentrations of the NOAA NS&T Program data were compared for 1984 through 1986, each year was significantly different than the other 2 years (p=0.05). The means for the 3 years were, 0.13 ppm in 1984, 0.53 ppm in 1985, and 0.33 ppm in 1986. Because of the short time span involved and because the mean cadmium concentration first increased and then decreased, no long-term trends were apparent from these data.

B. Biota

Cadmium concentrations have been measured in fish and bivalves by 15 surveys since 1971 (Table 2). Pooling all data (332 samples) for cadmium levels in mussels (*Mytilus edulis, M. californianus*) sampled between 1971 and 1986 shows the overall mean concentration in the Bay to be 7.41 ppm (Table 10). Cadmium levels have ranged from 0.8 to 34.4 ppm. The data indicate that the mean and median cadmium concentrations were relatively similar in San Pablo Bay, and the central and south Bay basins. However, since each basin is unevenly represented in the calculation of these means, results should be interpreted with caution. The mean cadmium concentration in San Francisco Bay mussels is slightly higher (1.9 times) than that of Tomales Bay mussels and lower than that of mussels from Bodega Head. The means and ranges in concentrations determined in surveys of mussels are compared with the grand mean for mussels in the Bay in Figure 20.

(1) Geographic Trends

The analyses of cadmium in Japanese littleneck clams (*Tapes semidecussata*) or soft-shell clams (*Mya arenaria*) by the U.S. EPA in 1972 (Shimmin and Tunzi, 1974), showed clams from Oakland Inner Harbor to be the most contaminated. These clams contained 0.58 ppm ww cadmium (approximately 5.1 ppm dw). These clams from peripheral areas (Oakland Inner Harbor and San Leandro Bay) contained higher levels of cadmium (generally, 2-5 ppm dw) than those from basin sites (1.1 - 2.2 ppm dw).

In 1973 and 1974, Anderlini et al. (1975a) sampled mussels (*Mytilus edulis*) from many sites in Mare Island Strait, Carquinez Strait, and Tomales Bay. Concentrations of cadmium from three of those sites were significantly different from others (p=0.05). Tomales Bay mussels contained the lowest levels of cadmium, which were significantly different from concentrations at sites in Mare Island Strait and Carquinez Strait. One sample of mussels from Selby Pier (in Carquinez Strait) contained the highest concentration (34.4 ppm) of cadmium, which was significantly different than those in 9 samples from Tomales Bay (2.7 ppm) and 21 samples from Mare Island Strait (3.5 ppm). Mussels from a site outside Mare Island Strait immediately south of Mare Island contained significantly higher concentrations (16.7 ppm) of cadmium than mussels from the sites in Mare Island Strait (p=0.05).

In 1974, Wyland (1975) sampled mussels (*Mytilus edulis*) from Tomales Bay and three sites in San Francisco Bay. Ten or more samples were collected per site. A wide range in concentrations was observed (Figure 20). Redwood Creek mussels had the highest single concentration (26.9 ppm) and the highest mean concentration of cadmium (16.63 ppm); significantly higher than the mean concentrations found in mussels from Tomales Bay (3.9 ppm), Berkeley Marina (4.5 ppm), and Coyote Point (7.1 ppm) (p=0.05).

The sampling of bay mussels (*Mytilus edulis*) in 1975 (Girvin et al., 1975) showed that the highest concentration of cadmium was found at Redwood Creek (10.9 ppm). Mussels from one site at Coyote Point also contained elevated cadmium levels (7.6 ppm). Peripheral areas (Islais Creek and Redwood Creek) produced mussels with higher levels of cadmium than most basin sites in central and south Bays. Mussels from all sites contained more than 2 ppm cadmium (Figure 20). Relatively uniform cadmium concentrations were found in clams (*Tapes japonica*) sampled during 1975 in the same study. The highest level was found at a Redwood Creek site (4.5 ppm) and the lowest level (1.8 ppm) was found in clams from Bayview Park near San Mateo.

In 1980, the sampling of bay mussels (*Mytilus edulis*) from 12 sites in the Bay by California Mussel Watch (Hayes et al., 1985) and by McCleneghan et al. (1982) showed highest levels (8.6 ppm) of cadmium to be detected at the Dumbarton Bridge . Resident mussels from Coyote Point and Point Isabel also contained elevated cadmium levels (7.2 and 7.3 ppm, respectively). Mussels sampled at the other sites contained from 3 to 6 ppm cadmium. Mussels sampled from sites in the south Bay generally contained higher levels of cadmium than those from central Bay or San Pablo Bay. Lowest levels of cadmium in mussels were detected at Bayshore Lagoon (3.31 ppm); they were significantly different than those found in mussels from Point Isabel and Burlingame (p=0.05).

Sampling of Japanese littleneck clams (*Tapes japonica*) in 1980 showed highest cadmium levels (4.77 ppm) in San Leandro Creek (Figure 21) (McCleneghan et al., 1982; Kinney and Smith, 1982). Clams from Foster City contained 3.9 ppm cadmium. Lowest levels of cadmium (0.9 ppm) were detected in clams collected off 3rd Avenue near San Mateo. Clams sampled by Kinney and Smith (1982) showed no differences in cadmium concentrations between sites (p=0.05). However, those clams (*Tapes* sp.) sampled by McCleneghan et al. (1982) near 3rd Avenue in San Mateo were significantly lower (p=0.05) in cadmium concentrations than the clams sampled at Coyote Point, Foster City, and Point Isabel.

In 1983, Luoma et al. (1984) sampled clams (*Corbicula* sp.) from several sites in Suisun Bay and in the Mendota Canal (Sacramento River). Cadmium concentrations in clams from the Mendota Canal were significantly lower than those from other sites (p=0.05).

The NS&T Program (NOAA, 1987a) analyzed cadmium in the livers of starry flounder (*Platichthys stellatus*) or white croaker (*Genyonemus lineatus*) from four sites in San Francisco Bay and a site in Bodega Bay in 1984 (Figure 22). The highest levels of cadmium were found in liver tissue of starry flounder taken from Southampton Shoal (19.57 ppm). Lowest concentrations were found in liver tissue of starry flounder from San Pablo Bay (0.56 ppm), although these differences were not significantly different (p=0.05). The sites and fish species sampled by the NS&T Program have apparently not been sampled for cadmium in other surveys.

In 1985 and 1986, the California Mussel Watch Program (Hayes and Phillips, 1985, 1986) analyzed cadmium in coastal mussels (*M. californianus*) transplanted to10 sites in San Francisco Bay and in resident mussels from Bodega Head (Figure 23). Highest levels of cadmium were found in mussels transplanted to Oakland Inner Harbor (11.74 ppm). Mussels from Santa Fe Channel, Alameda Yacht Harbor, and the San Mateo Bridge contained more than 7 ppm cadmium. Mussels transplanted to other peripheral areas had cadmium concentrations similar to those transplanted to basin sites. Mussels transplanted to sites in the south Bay had cadmium levels higher than those transplanted to central Bay or San Pablo Bay sites.

In 1986, the NOAA NS&T Program analyzed cadmium in resident mussels (*M. edulis*) from San Mateo Bridge, Dumbarton Bridge, Tomales Bay, and Bodega Head (Figure 23) (Boehm et al., 1987). Levels of cadmium were highest in mussels from Dumbarton Bridge (6.97 ppm). Cadmium concentrations were below the grand mean value for the Bay (Figure 20). There were no significant differences among sites (p=0.05). Results generated by the NS&T Program are generally lower than mean levels of cadmium detected in mussels by other investigations (e.g., Hayes et al., 1985) at sites near NS&T Program sites. At the San Mateo Bridge site Hayes et al. (1985), Hayes and Phillips (1986, 1987), and Risebrough et al. (1978) detected a mean level of 11.11 ppm cadmium (with a range of 5.2-18.9 ppm), while the NS&T Program detected 5.73 ppm in mussels sampled nearby. At the Dumbarton Bridge site, Hayes et al. (1985) , Hayes and Phillips (1986, 1987), and Risebrough et al. (1978) detected a mean concentration of 10.05 ppm in mussels sampled between 1976 and 1985, while the NS&T Program detected 6.97 ppm in mussels. At Bodega Head, other surveys (Hayes et al., 1985; Hayes and Phillips (1986, 1987; Farrington et al., 1982) detected a mean level of 10.14 ppm in mussels sampled between 1976 and 1986, compared to 3.83 ppm detected by the NS&T Program. In Tomales Bay, Hayes et al. (1985), Anderlini et al. (1975a, b), and Wyland (1975) detected a mean level of 3.71 ppm in mussels, whereas the NS&T Program detected 5.53 ppm in mussels sampled in 1986.

(2) Temporal Trends

Resident bay mussels (*M. edulis*) have been resampled at three sites since 1975 or 1980. Cadmium concentrations in mussels from Foster City, or nearby on the San Mateo Bridge, remained at 5 to 6 ppm in 1975, 1982, and 1986 (Girvin et al., 1975; Hayes et al., 1985; Boehm et al., 1987). Sampling at Redwood Creek (and at two sites nearby) indicated a slight decline in cadmium from 10.9 ppm in 1975 to 5.6 ppm in 1980 to 6.4 ppm in 1982. Cadmium concentrations in mussels at the Dumbarton Bridge have remained near 8 ppm in 1980, 1982, and 1986.

Clams (*Tapes* sp., *Mya arenaria*) have been resampled in two areas of San Francisco Bay since 1972 (Shimmin and Tunzi, 1974; Girvin et al., 1975; McCleneghan et al., 1982). Samples from Foster City indicate that cadmium levels may have increased slightly in Japanese littleneck or soft-shell clams from 1 ppm in 1972 to 2.9 ppm in 1975, and 3.9 ppm in 1980. Cadmium in clams taken from Albany Hill or nearby at Point Isabel remained at 2 to 3 ppm during 1972, 1975, and 1980.

Transplanted mussels (*Mytilus californianus*) have been resampled by Hayes et al. (1985) and Hayes and Phillips (1986, 1987)) at eight sites in San Francisco Bay annually since 1980 (Figure 24). No changes in cadmium levels were apparent at four of the eight sites. At Point Pinole, Angel Island, Treasure Island, and Dumbarton Bridge, cadmium levels have declined in transplanted mussels to less than half the levels reported in the first year of sampling. The annual means and ranges in concentrations for all sites have declined slightly from 1981 to 1986 (Figure 24). At Bodega Head, cadmium concentrations doubled from about 7 ppm in 1977 to 16 ppm in 1980, then gradually declined to about 6 ppm in 1985, corresponding to the decline at four sites in San Francisco Bay. These changes were not significant (p=0.05).

C. Summary

Like mercury concentrations, cadmium concentrations in the sediments of San Francisco Bay and its environs display a small-scale patchiness and a large-scale homogeneity. This pattern is shown by the large range of individual sample concentrations of cadmium (0.02 to 17.3 ppm), a difference of 865 times (Table 8), and the small range of mean cadmium concentrations based on study and year (0.13 to 3.37 ppm), a difference of 26 times (Figure 15).

Table 11 gives the means, standard deviations, medians, and ranges of cadmium concentrations in sediments from the four basins and selected peripheral areas based on data from all the studies compiled for this report. It also includes the number of samples taken at each area and the years in which sampling took place. While the table orders the areas from highest to lowest mean, any comparisons must be performed with extreme caution because of differences in sampling and analytical methodologies, time of sampling, and number of samples taken at each area. Possibly, the most significant statistics in Table 11 are the ranges that show a high degree of overlap for the areas sampled, both basin and peripheral areas. Six peripheral areas (China Basin, Redwood City Harbor, Islais Creek, Coyote Creek, Mare Island Strait, Guadulupe Slough) stand out as having had relatively highly contaminated sediments. A possible pattern of increasing cadmium concentrations from north to south in the four basins is suggested by the means and medians. The mean for China Basin (4.9 ppm) exceeds that for reference areas (Tomales Bay, 0.37 ppm; Bodega Bay, 0.23 ppm) by factors of 21 and 13, respectively. Five of six of the most highly contaminated peripheral areas are adjacent to south Bay. The grand mean for the Bay (1.06, Table 8) exceeds the means for Tomales Bay and Bodega Bay by factors of 2.9 and 4.6, respectively.

While the overall data indicate that cadmium concentrations in the sediments of San Francisco Bay display a small-scale patchiness and a large-scale homogeneity, the overall means for the basins and the peripheral areas (Table 8) seem to indicate that the basins are slightly less contaminated than the peripheral areas. However, when individual studies were analyzed, no such pattern was apparent. Also, when the areas in Table 11 were compared, both the three areas with the highest mean cadmium concentrations and the three with the lowest were all peripheral areas, while the means for the basins were interspersed with the rest of the peripheral area means.

The sediment data also failed to indicate a pattern of any major long-term temporal trends other than quarterly fluctuations in cadmium concentrations as observed in the SBDA study. In the SBDA study, mean cadmium concentrations underwent greater than a sixfold increase from one quarterly sampling period to another and then displayed a similar decrease two quarters later. Aside from the short episode in 1983, the SBDA data do not suggest a longer term trend of change from 1982 through 1986. The COE data indicated a pattern of small decreases in five areas over a 7- to 9-year period, but this pattern may be due, in part, to the effects of sampling different sites each year.

Mean and median concentrations in mussels during the period 1971-1986 were very similar among the three basins for which there are data. These values are also similar to the concentrations observed in 1985-86 at reference sites in Tomales Bay and at Bodega Head. However, some samples off Angel Island in central Bay and off Point Pinole in San Pablo Bay and at the Selby Pier in Carquinez Strait in the early 1980s were relatively contaminated. Some mussel samples taken in peripheral harbors and marinas also showed high cadmium concentrations. In addition, clam samples from sites in south Bay below the San Mateo Bridge were relatively contaminated. Very high concentrations were found in fish from Southhampton Shoal in 1984; otherwise, low levels were found in other fish samples.

The mean levels of cadmium contamination in sediments have apparently decreased since the mid 1970s. This decrease is supported by yearly Bay-wide data as well as data from individual sites.

A general pattern of slightly decreasing mean cadmium concentrations is evident in mussel tissues, however, the differences between years are not significant. Data from four individual mussel sampling sites in the Bay indicate that cadmium concentrations have decreased since 1980; no changes are apparent at other sites. Data from other biota are inconclusive thus far regarding temporal trends. The relatively high within-site variability of many of the surveys and the short-term records from most surveys precludes determining Bay-wide, long-term temporal trends. For example, Luoma et al. (1987) have shown large within-year and annual variations in cadmium concentrations in *Corbicula sp.* in Suisun Bay.

Historical mean concentrations of cadmium in sediments sampled from 1972 through 1986 in San Francisco Bay are compared in Figure 25 with means of three samples each for the NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper-case print. The NS&T Program sites are listed in lower-case print. Those from the 1984 Benthic Surveillance Project are designated by "BS" after the site name; those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold, lower-case print. The mean overall concentration for the Bay (1.06 ppm) was relatively high compared to the 1984 and 1986 NS&T Program Pacific Coast sites. China Basin was particularly contaminated, being similar to a site off Palos Verdes near Los Angeles. Among the 1984 and 1986 NS&T Program sites, most of those in the Bay ranked low (14th to 46th) in cadmium levels. The two reference sites, Tomales Bay and Bodega Bay, ranked 20th and 36th, respectively. Also, the historical means for south Bay and all peripheral areas in the Bay were relatively high.

The historical mean concentrations of cadmium in mussels collected in San Francisco Bay from 1972 tthrough 1986 are compared in Figure 26 with means from the three samples of mussels each from the NS&T Program Pacific Coast sites sampled in 1986. The historical areas are designated in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located within the Bay are listed in bold print. The historical means for San Francisco Bay were relatively high compared to the Pacific Coast sites. The historical grand mean for the San Pablo Bay basin exceeded the 1986 mean for all the Pacific Coast sites. The grand mean for San Francisco Bay and the overall mean for south Bay were only exceeded by mussels at a site at Point Delgada in northern California. Coastal promontories, such as Cape Flattery and Point Delgada may experience inputs of cadmium from upwelling. The Redwood Creek area has been highly contaminated relative to the remainder of the Bay and relative to the 1986 NS&T Program sites. Among the 1986 NS&T Program sites, two sites in the Bay (Dumbarton Bridge, San Mateo Bridge) were ranked second and fifth in cadmium contamination. The two reference sites, Tomales Bay and Bodega Head, were ranked 6th and 16th, respectively.

Table 8. Bay-wide means, standard deviations, medians, and ranges of cadmium concentrations in surficial sediments of San Francisco Bay based on data collected by many investigators from 1971 through 1987 from the four basins and peripheral harbors and waterways (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	1.06	1.16	0.71	0.02-17.3	999
BASINS	0.94	1.25	0.69	0.02-17.3	256
PERIPHERY	1.10	1.13	0.76	0.03-8.6	743

Table 9. Yearly ranking of areas, from highest to lowest cadmium levels, sampled by the COE from 1971 through 1979, based on the ANOVA and Scheffé's F-test of the log-transformed data (bars connect those areas which are not significantly different at p=0.05) .

1971* ALAMEDA NAS SAUSALITO CHNNL REDWOOD CITY HBR SAN BRUNO CHNNL ISLAIS CREEK	**1972** REDWOOD CITY HBR MARE ISLAND STRAIT OAKLAND OUTER HBR RICHMOND HBR ALAMEDA NAS PT MOLATE	**1973** ALAMEDA NAS PETALUMA CHNNL PETALUMA RIVER
1974 ISLAIS CREEK OAKLAND INNER HBR PT MOLATE ALAMEDA NAS MARE ISLAND STRAIT RICHMOND HBR CHNNL RICHMOND HBR OAKLAND OUTER HBR	**1975** MARE ISLAND STRAIT RICHMOND HBR CHNNL PINOLE SHOALS OAKLAND INNER HBR OAKLAND OUTER HBR	**1976** BERKELEY BRKWTR** ALAMEDA NAS MARE ISLAND STRAIT RICHMOND HBR CHNNL OAKLAND INNER HBR SUISUN BAY** PETALUMA CHNNL OAKLAND OUTER HBR
1977 OAKLAND OUTER HBR RICHMOND HBR CHNNL OAKLAND INNER HBR MARE ISLAND STRAIT	**1978** OAKLAND INNER HBR OAKLAND OUTER HBR RICHMOND HBR CHNNL ALAMEDA NAS MARE ISLAND STRAIT	**1979** MARE ISLAND STRAIT OAKLAND OUTER HBR OAKLAND INNER HBR RICHMOND HBR

* Those areas with less than two samples were excluded from the analysis (Mare Island Strait and Point Molate).

** In 1976, Suisun Bay and Berkeley Breakwater were not significantly different, possibly due to the small sample sizes of 3 and 4, respectively.

Table 10. Means, medians, and ranges in cadmium concentrations in mussels (Mytilus edulis and peripheral or Mytilus californianus) collected by many investigators from the four basins and peripheral areas of San Francisco Bay,1971-86 (ppm dw).

AREA/SITE	MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY					
BASIN	12.50	-	-	-	1
SAN PABLO BAY					
BASIN	10.83	7.77	9.90	2.4-34.4	33
PERIPHERAL-MARE ISL. ST.	4.81	2.49	3.90	2.2-10.9	24
CENTRAL BAY					
BASIN	6.10	2.20	5.60	1.8-15.0	105
PERIPHERAL-RICHMOND HBR.	7.78	2.21	7.40	5.5-10.8	4
PT. ISABEL	4.97	0.22	-	4.8-5.1	2
BERKELEY MARINA	4.36	1.79	4.05	1.4-7.0	12
ALL PERIPHERAL	5.19	2.23	5.31	1.4-10.8	18
SOUTH BAY					
BASIN	7.27	3.24	6.25	0.8-18.9	98
PERIPHERAL-ISLAIS CREEK	5.30	-	-	-	1
ALVISO SLOUGH	13.50	-	-	-	1
ALAMEDA YACHT HBR.	11.47	4.00	-	8.64-14.3	2
OAKLAND INNER HBR.	6.87	3.27	5.49	4.74-11.74	4
OAKLAND OUTER HBR.	1.80	-	-	-	1
BAYSHORE LAGOON	3.30	0.01	-	3.30-3.30	2
PALO ALTO YACHT	10.13	0.83	10.40	9.2-10.8	3
REDWOOD CREEK	11.35	5.71	9.05	5.6-26.9	32
BELMONT SLOUGH	17.20		-	-	1
NEWARK SLOUGH	12.10	-	-	-	1
ALL PERIPHERAL	10.36	5.50	9.00	1.8-26.9	47
ALL SAN FRANCISCO BAY	7.41	4.39	6.00	0.8-34.4	332
TOMALES BAY	3.86	1.43	3.70	1.7-7.2	37
BODEGA HEAD	9.71	3.27	9.50	2.5-16.3	53

Table 11. Means, standard deviations, medians, and ranges of cadmium concentrations in the surficial sediments of San Francisco Bay for the four basins, selected peripheral areas, and the NOAA NS&T Program reference sites based on data collected by many investigators from1970 through 1987 (ppm dw). The Bay sites are ordered from highest to lowest mean.

AREA	YEARS SAMPLED	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
CHINA BASIN	79	4.93	2.73	4.50	2.10 - 8.6	4
REDWOOD CITY HARBOR	71-74	2.47	1.69	1.40	0.47 - 4.8	15
ISLAIS CREEK	71, 74, 79, 85	2.23	1.68	2.40	0.43 - 6.5	18
COYOTE CREEK	82-86	1.94	1.55	1.53	0.60 - 6.7	20
MARE ISLAND STRAIT	71-79	1.54	1.32	1.20	0.20 - 8.3	194
GUADALUPE SLOUGH	82-86	1.45	0.87	1.14	0.60 - 3.7	20
SOUTH BAY	71, 73, 74, 79, 80, 82-86	1.44	2.02	1.03	0.10 - 17.3	81
ALAMEDA NAS	71-74, 76, 78	1.31	1.01	1.00	0.20 - 4.2	59
POINT MOLATE	71, 72, 74	1.07	0.47	0.80	0.48 - 1.9	17
HUNTERS POINT NS	72-74, 86, 87	0.96	0.21	1.00	0.60 - 1.4	20
SAN LEANDRO BAY	80-81	0.85	1.11	0.50	0.40 - 4.6	15
CENTRAL BAY	71, 73, 74, 76, 80, 81, 84-86	0.79	0.40	0.75	0.02 - 2.2	77
SAN PABLO BAY	73, 75, 76, 84-86	0.71	0.54	0.53	0.04 - 2.0	51
0AKLAND INNER HARBOR	73-79	0.67	0.77	0.35	0.10 - 3.2	65
RICHMOND HARBOR	72-79	0.65	0.43	0.60	0.10 - 2.6	104
CASTRO COVE	81	0.62	0.39	0.52	0.04 - 1.5	43
OAKLAND OUTER HARBOR	72-81	0.55	0.43	0.50	0.05 - 2.3	70
CARQUINEZ STR./SUISUN BAY	73, 74, 76, 83	0.52	0.57	0.24	0.03 - 2.1	46
BERKELEY MARINA	80-81	0.49	0.03	0.50	0.40 - 0.5	15
GALLINAS CREEK	81	0.47	0.65	0.15	0.03 - 2.8	27
CORTE MADERA	81	0.38	0.28	0.30	0.04 - 1.1	24
TOMALES BAY	86	0.37	0.04	0.36	0.33 - 0.4	3
BODEGA BAY	84, 85	0.23	0.20	0.25	<.001 - 0.5	6

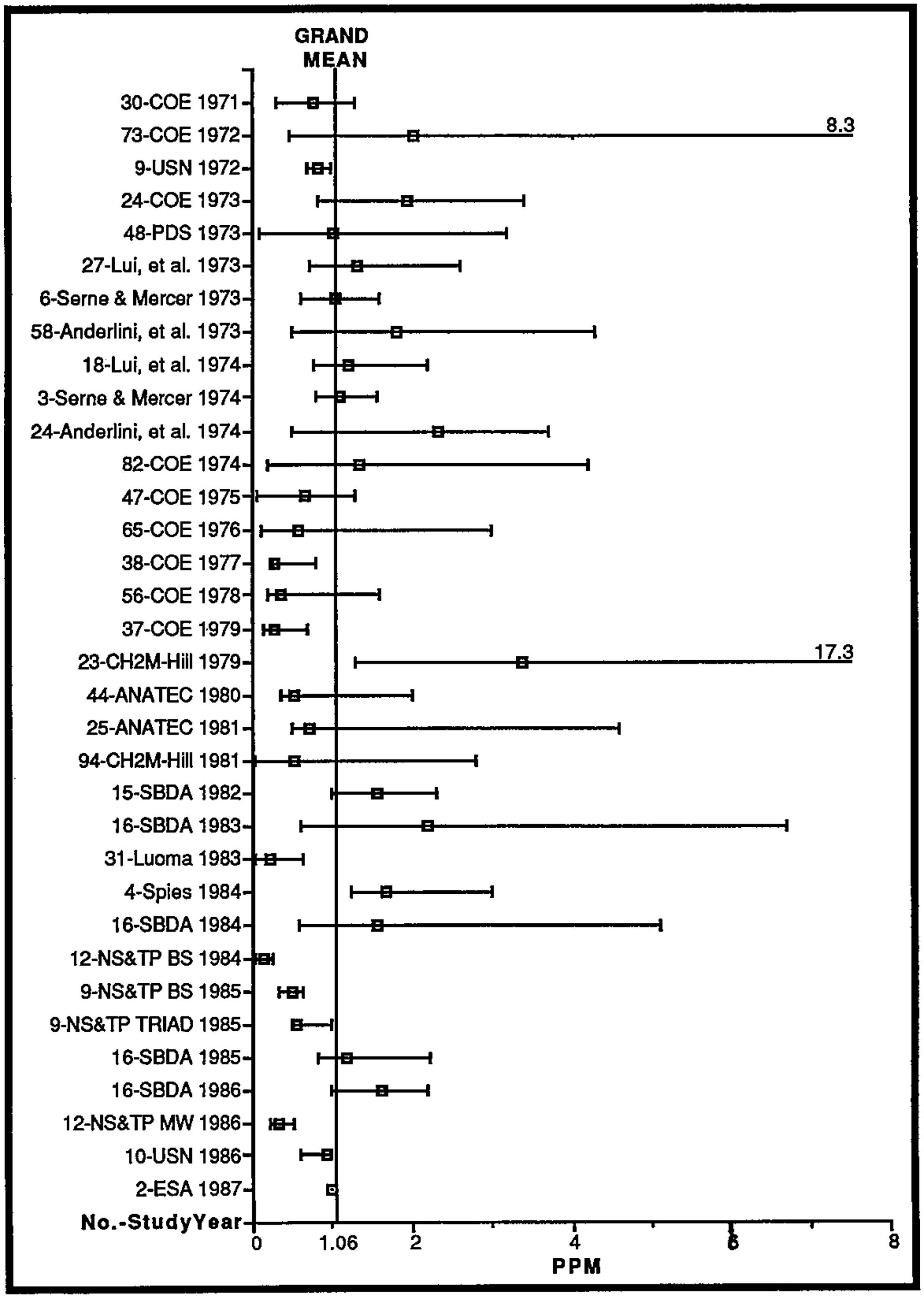


Figure 15. Mean concentration of cadmium in the surficial sediments of San Francisco Bay by study and year compared to the grand mean for the Bay (ppm dw) (No.=number of samples, bars represent the range).

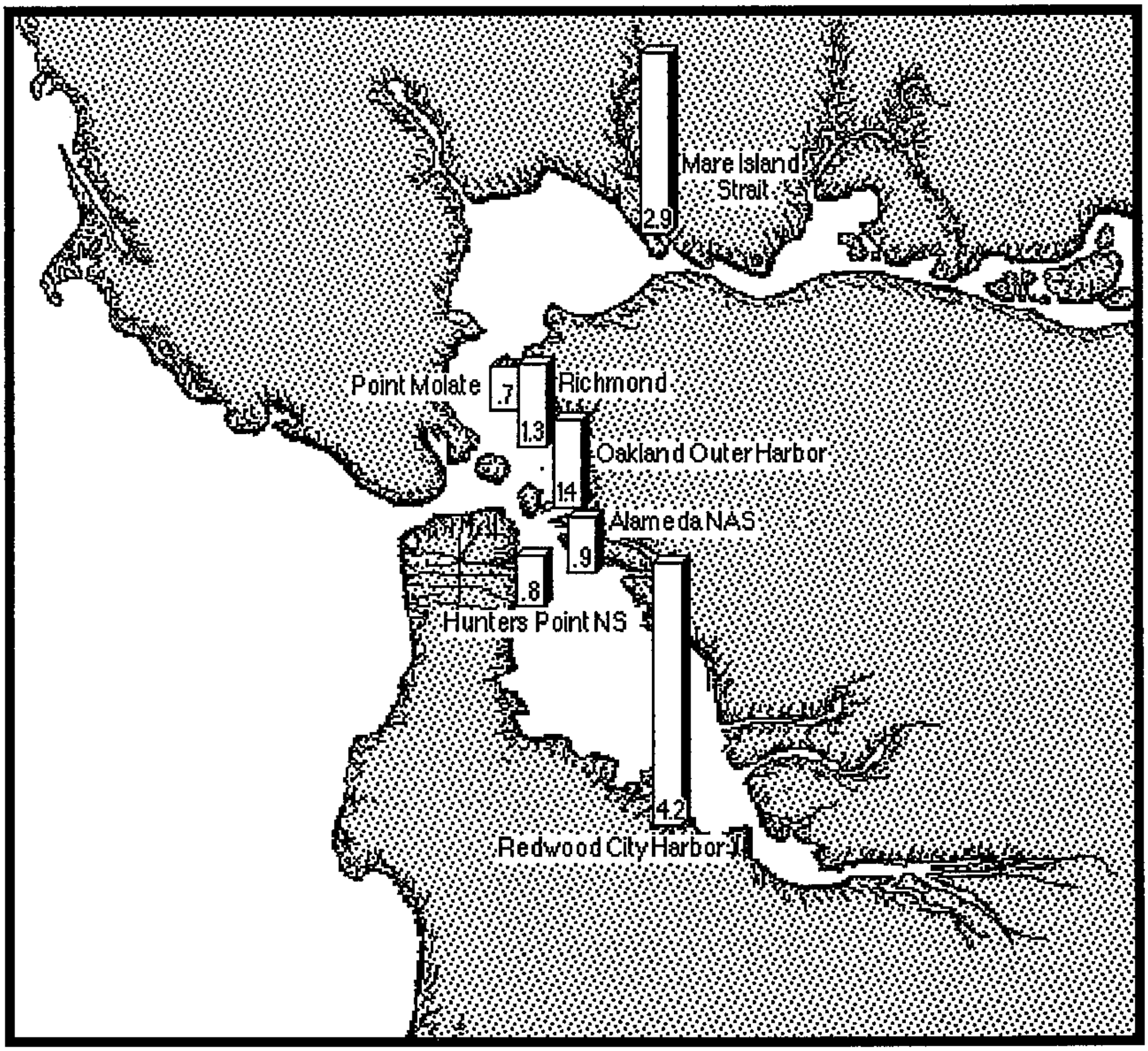


Figure 16. Mean cadmium concentrations, in ppm dw, based on 1972 dredging studies (COE, 1979a; U.S. Navy, 1972).

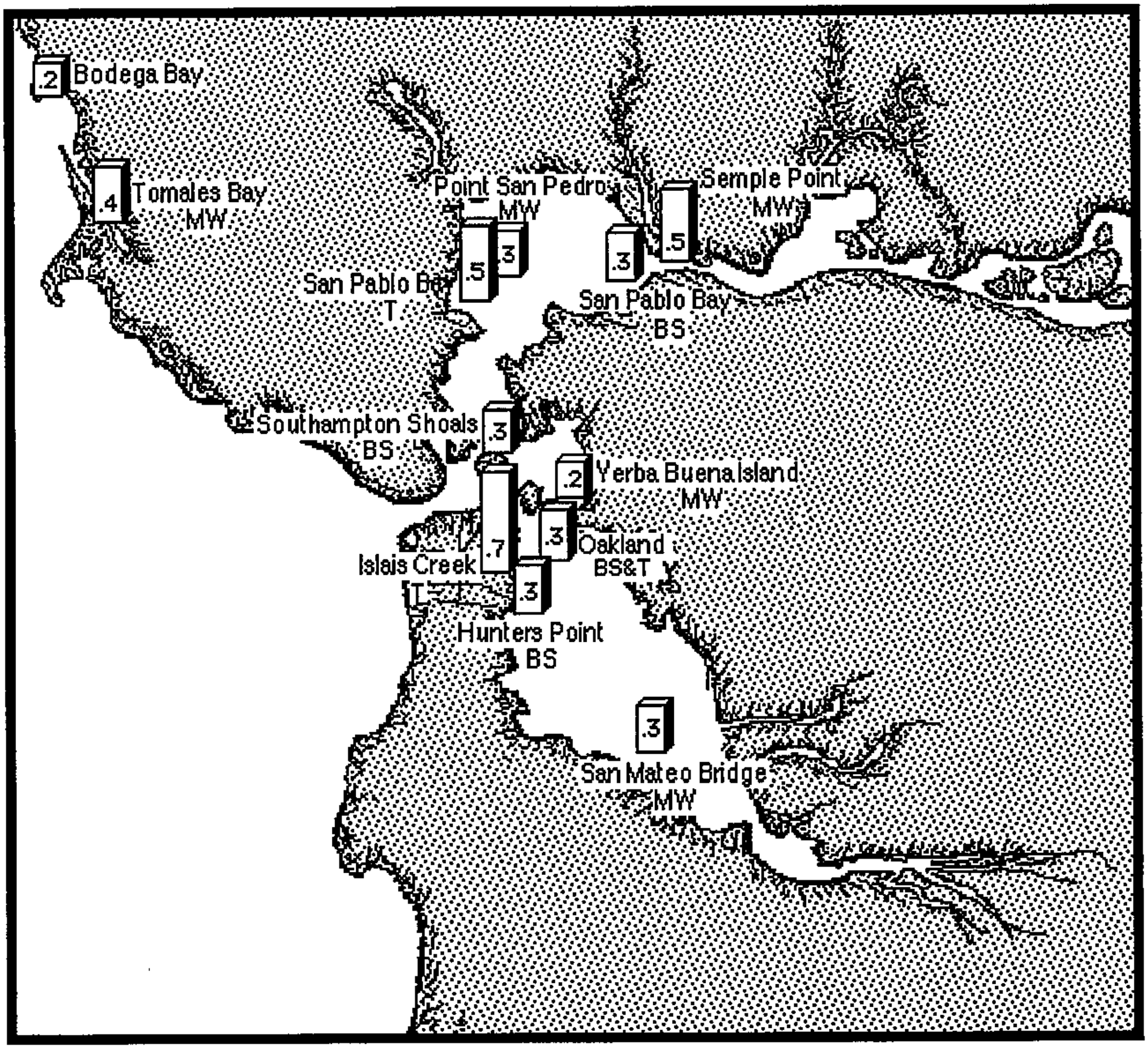


Figure 17. Mean cadmium concentrations in the surficial sediments for 1984-86, in ppm dw, based on NOAA NS&T Program data (BS=Benthic Surveillance, MW=Mussel Watch and T=Sediment Quality Triad study) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986) .

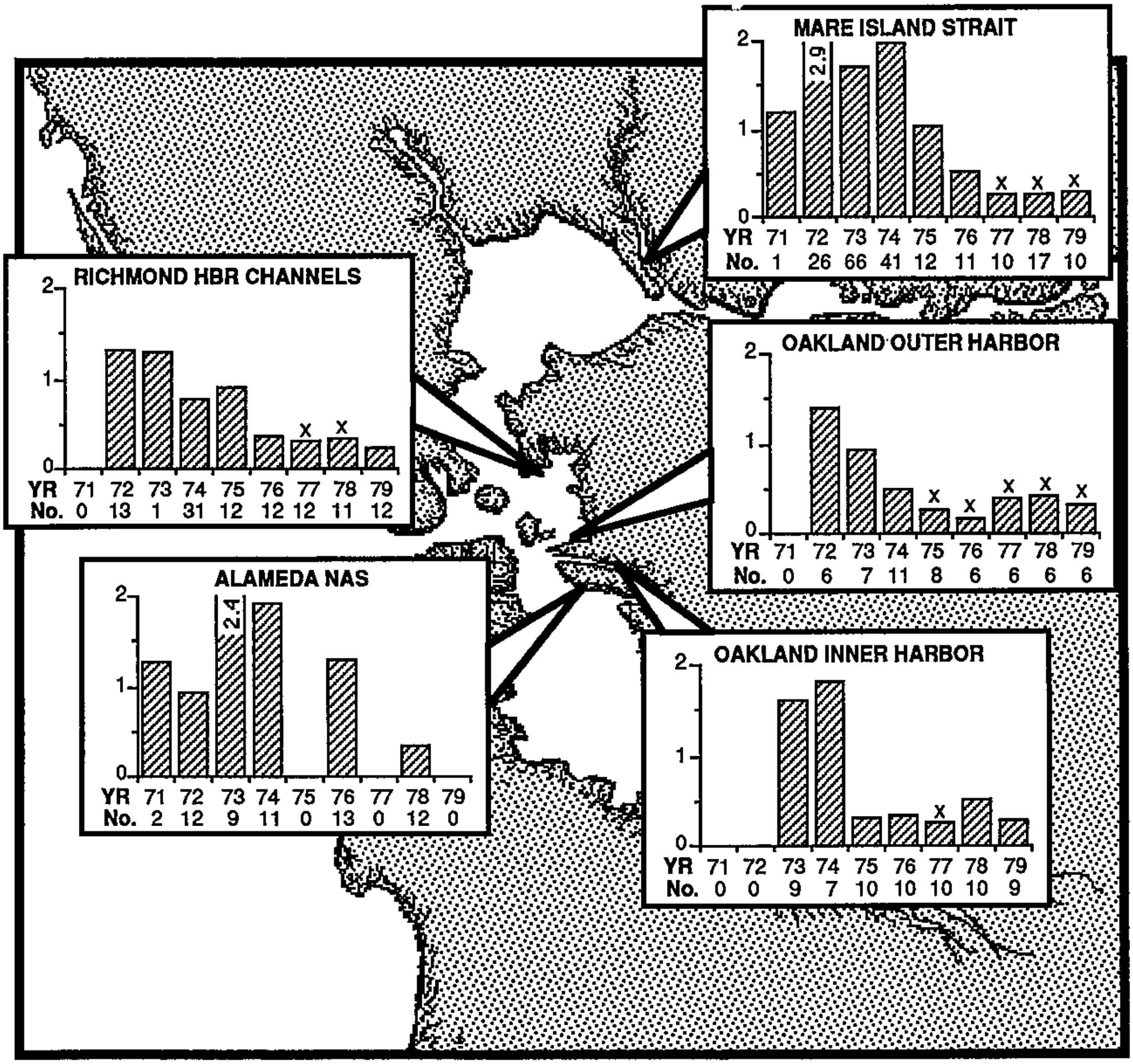


Figure 18. Mean cadmium concentrations, in ppm dw, at five sites from 1971 through 1979, based on dredging studies. An X indicates that all values were below the detection limits and half the detection limit was used for calculating the mean. The detection limits were: 1975:0.5, 1976:0.2, 1977:0.5-0.6, 1978:0.5-0.8 and 1979:0.4-0.6 (COE, unpublished data sheets1975-79, 1979b).

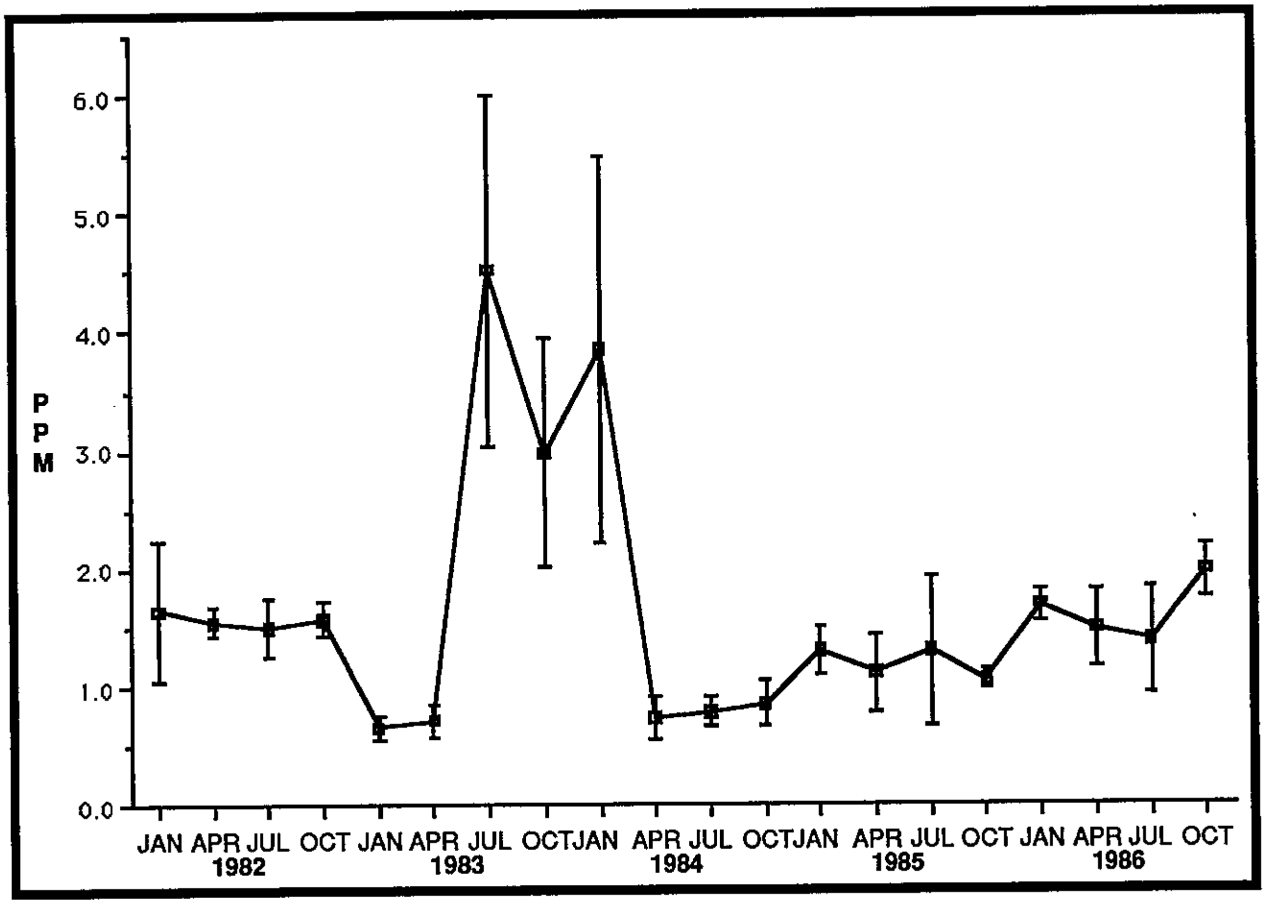


Figure 19. Monthly mean cadmium concentration in the surficial sediments at the four sites in the southern end of south Bay sampled by the SBDA from 1982 to 1986 (bars represent one standard deviation) (Stevenson et al., 1987).

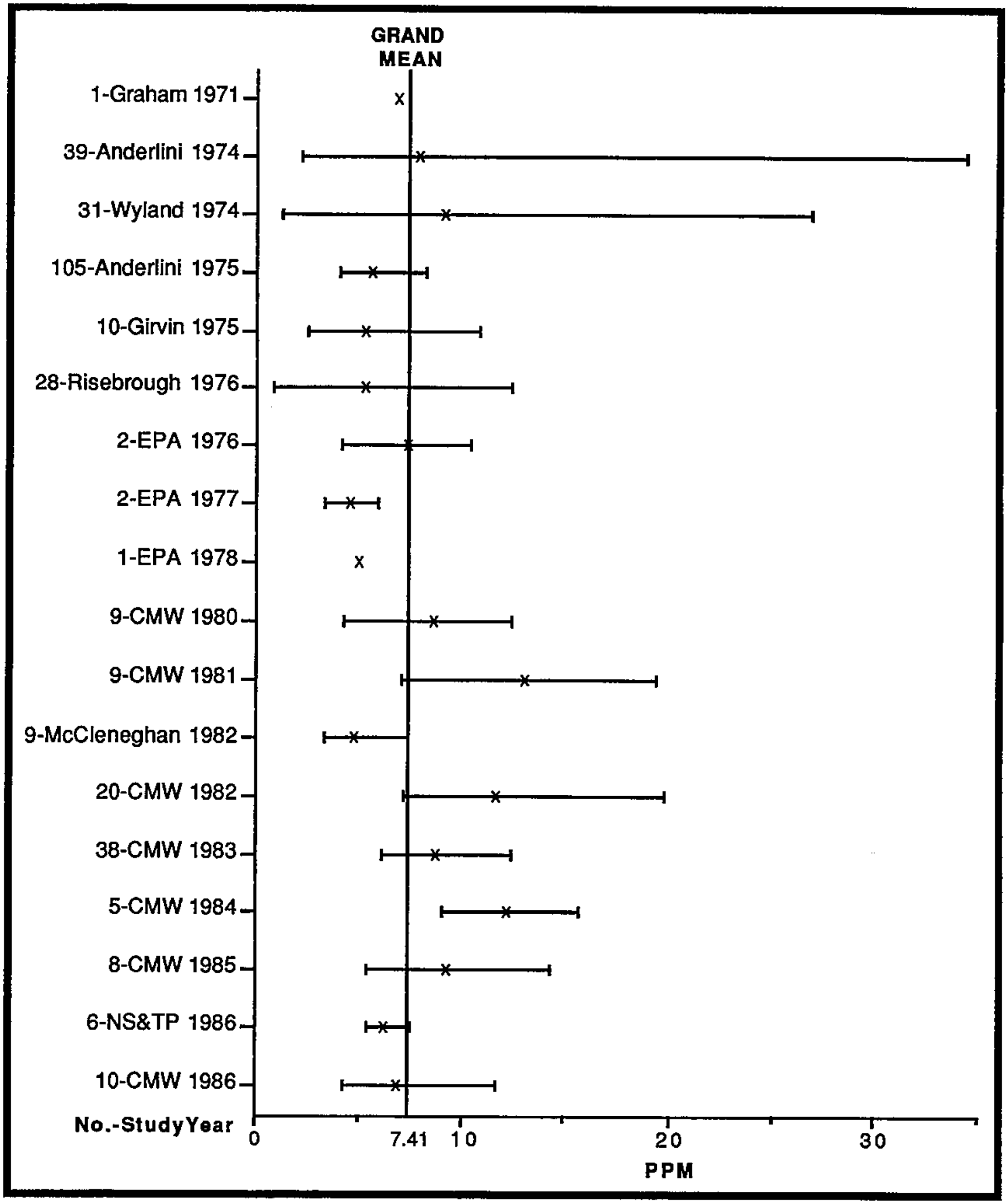


Figure 20. Mean concentration of cadmium in mussels (Mytilus edulis or Mytilus californianus) by study and year in ppm dw (No.=number of samples, bars represent the range).

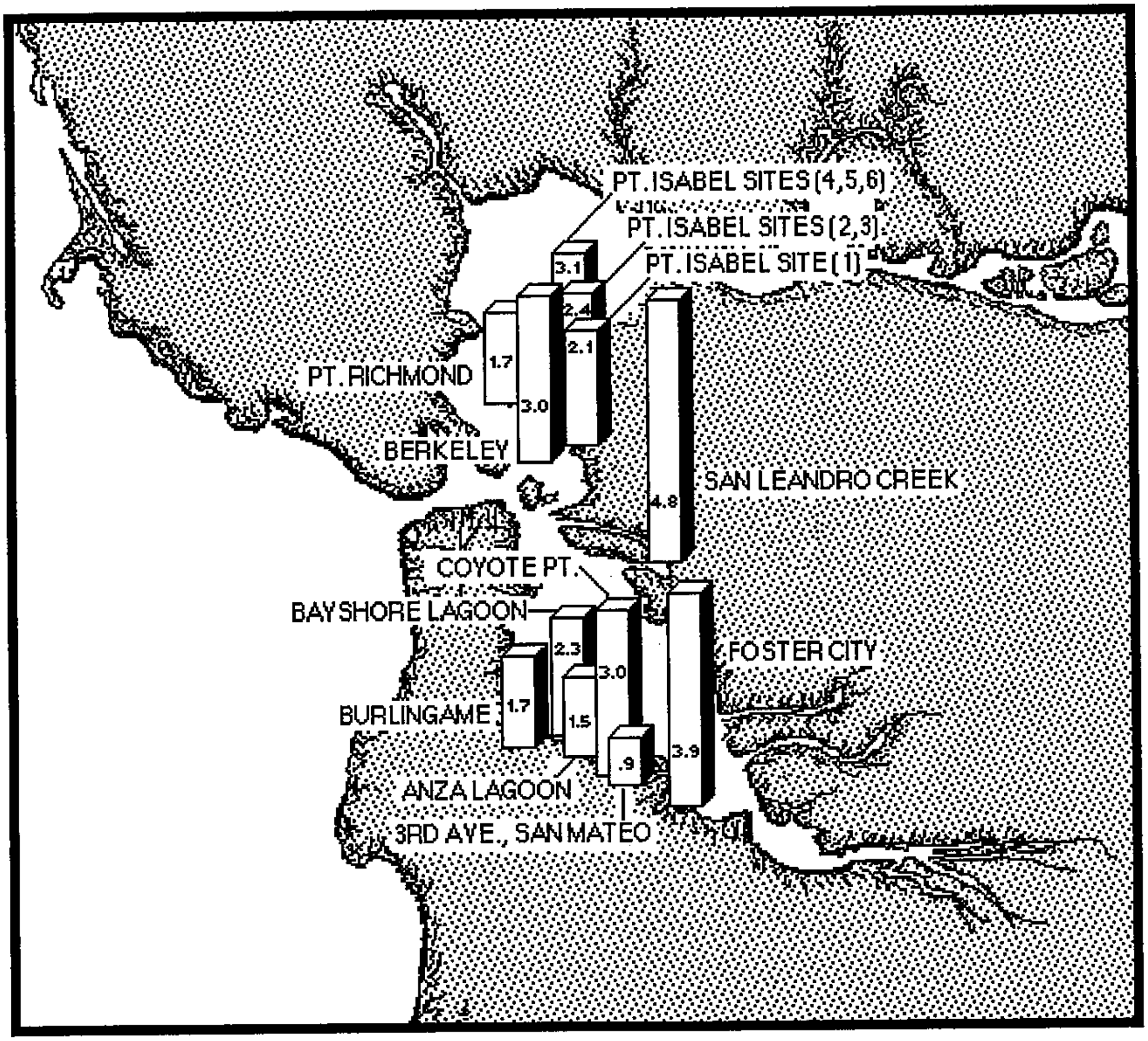


Figure 21. Concentration of cadmium in Japanese littleneck clams (Tapes japonica) in 1980 (ppm dw) (Hayes et al., 1985; McCleneghan et al., 1982).

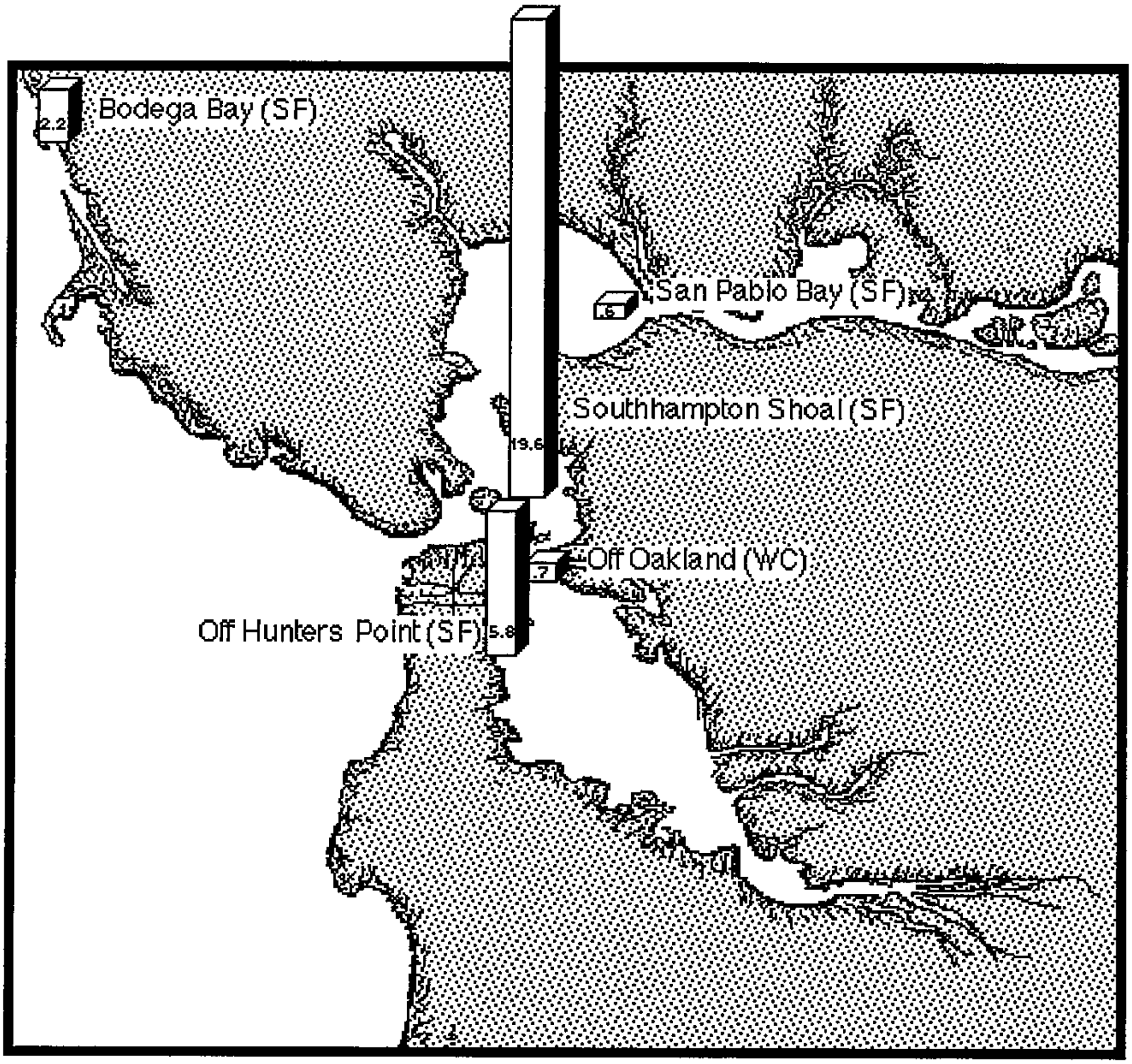


Figure 22. Cadmium concentrations in liver tissue of starry flounder (SF), Platichthys stellatus, and white croaker (WC), Genyonemus lineatus, in 1984 (ppm dw)(NOAA, 1987a).

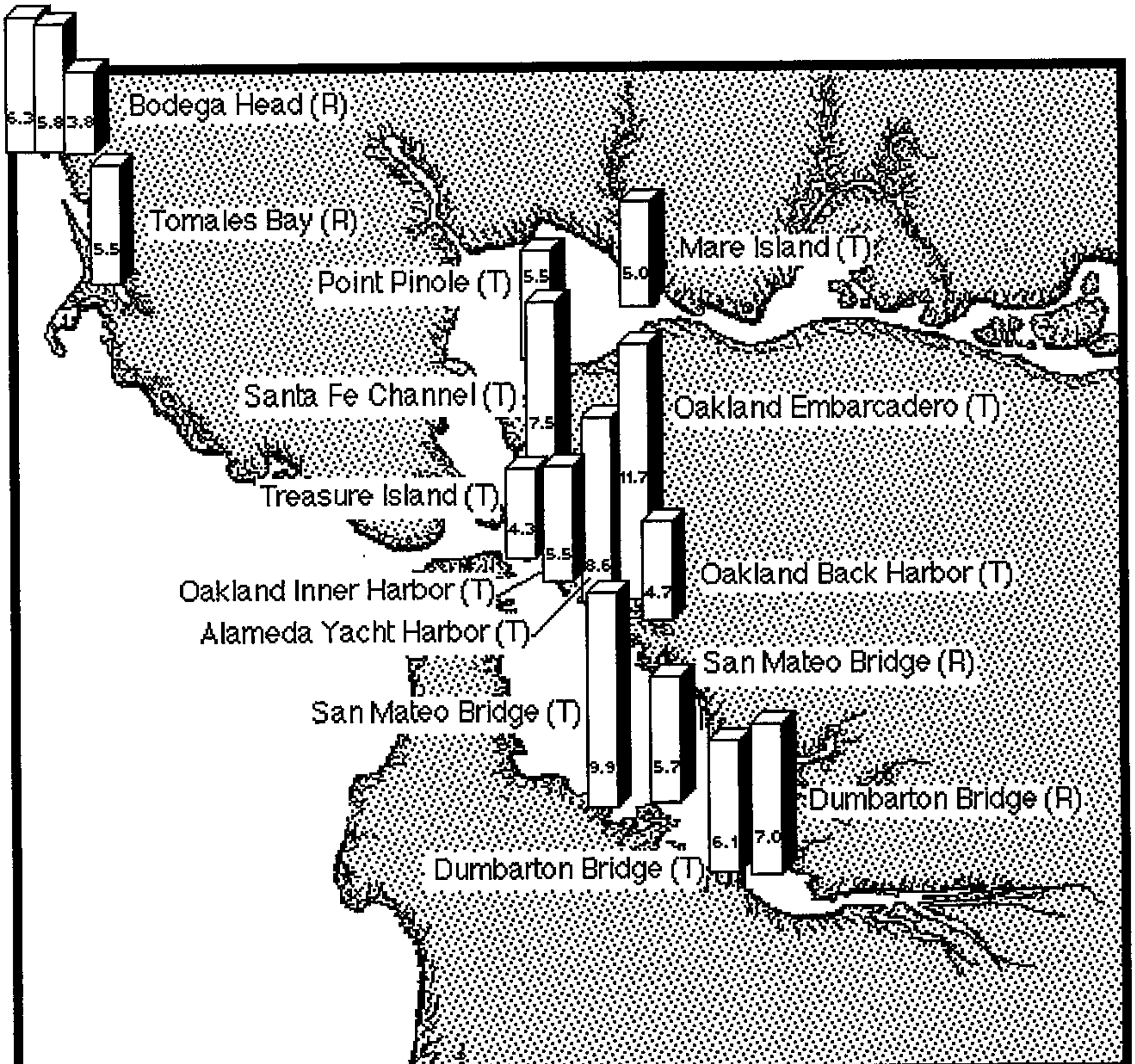


Figure 23. Cadmium concentrations in transplanted (T) coastal mussels, Mytilus californianus, and resident (R) Bay mussels, M.edulis, sampled in 1985-86 by the California Mussel Watch Program (Hayes and Phillips, 1987) and the NS&T Program (Boehm et al., 1987).

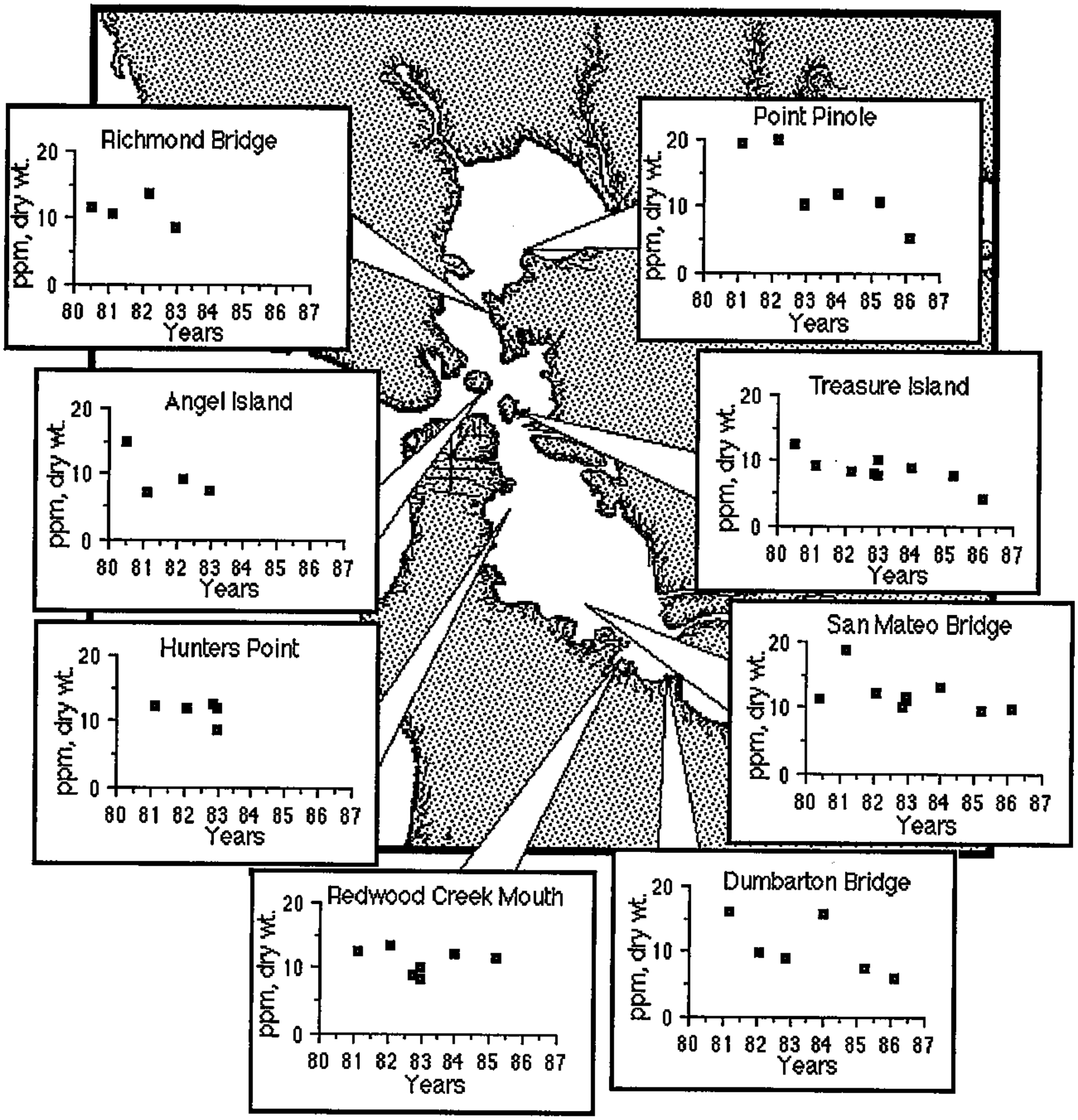


Figure 24. Temporal trends in cadmium concentrations in transplanted mussels (Mytilus californianus), 1980-86 (Hayes et al., 1985; Hayes and Phillips, 1986,1987).

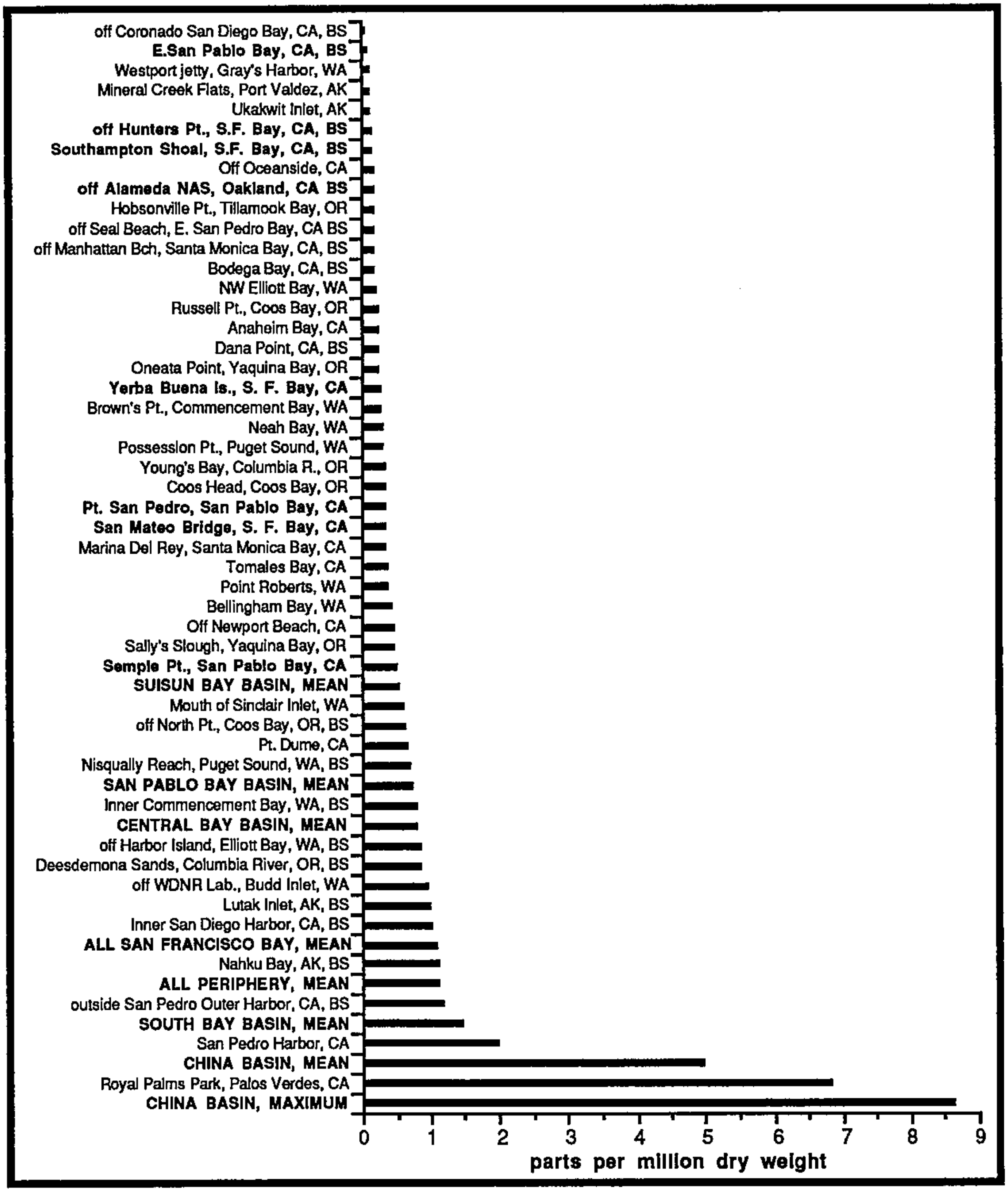


Figure 25. Comparison of cadmium concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Tables 8 and 11), to concentrations in the surficial sediments of NOAA's NS&T Program 1984 Benthic Surveillance (NOAA, 1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name .

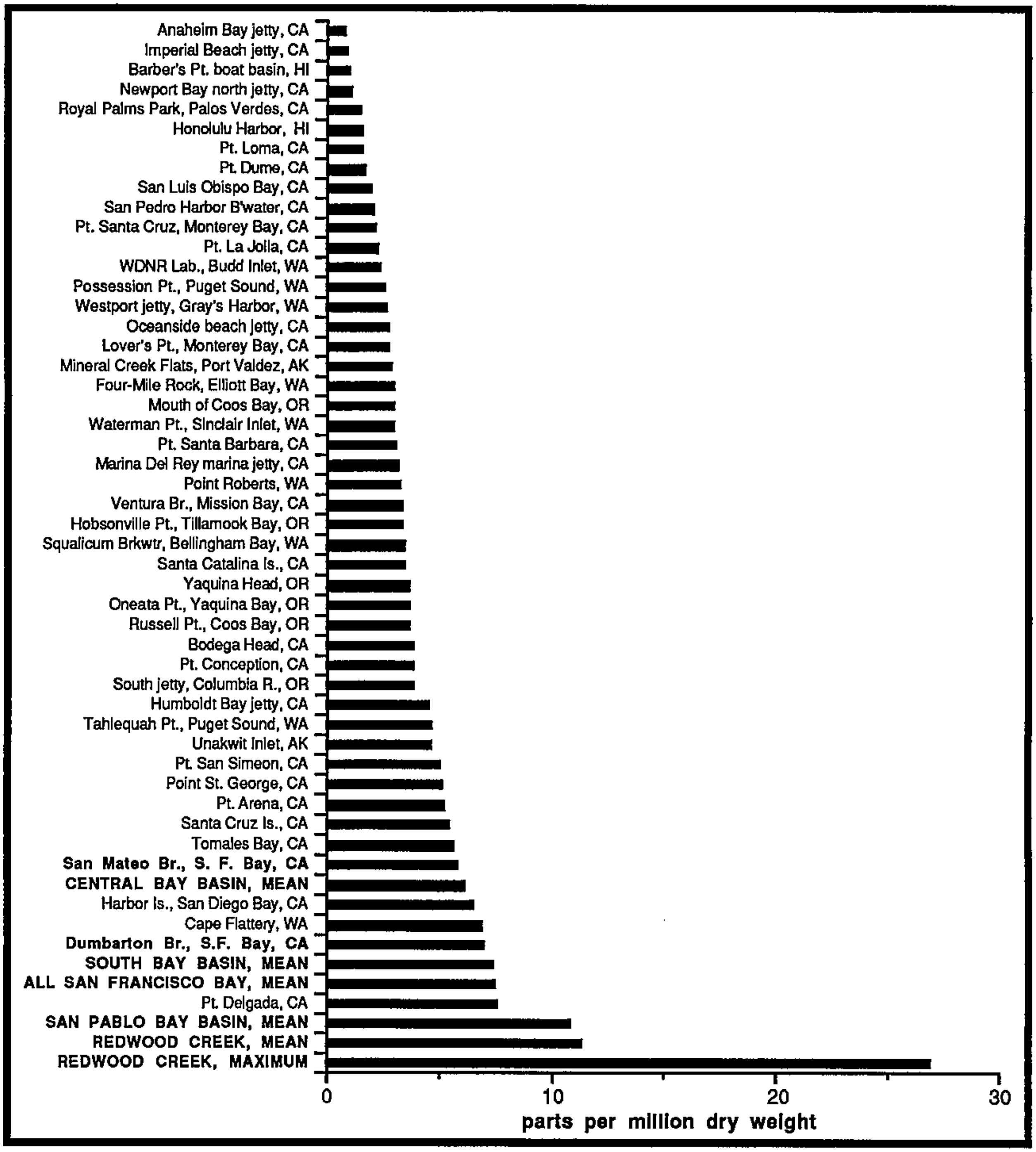


Figure 26. Mean cadmium concentrations in resident mussels (Mytilus edulis, M. californianus) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels (Mytilus edulis, M. californianus) calculated from 1972-1986 data for San Francisco Bay (from Table 10). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

5

GEOGRAPHIC AND TEMPORAL TRENDS IN COPPER CONTAMINATION

A. Sediments

Data have been compiled by numerous investigators on the concentration of copper in the surface sediments of San Francisco Bay and its environs for the years 1970 through 1987 (Table 1). Based on more than 800 samples collected throughout the system, the grand mean concentration of copper in San Francisco Bay sediments for the last 18 years was 51 ppm with a standard deviation of 58 ppm and a range from less than 1 to 1,500 ppm (Table 12). The vast majority of the copper values (89 percent) were between 10 and 100 ppm inclusive; 6 percent were less than 10 ppm, while 5 percent were greater than 100 ppm (only one sample had a concentration in excess of 300 ppm). The median value was 46 ppm. Copper concentrations have been noticeably higher in peripheral areas than in the basins.

(1) Geographic Trends

The most thorough study of copper contamination in San Francisco Bay was conducted by the USGS in 1970 (Peterson et al., 1972). The USGS analyzed 207 samples of the upper 6 inches of sediment from throughout the Bay area for copper and other metals. They found an overall mean copper concentration of 44 ppm with a standard deviation of 107 ppm and a range from 5 to 1,500 ppm (Figure 27). If the single sample containing the highest concentration of copper (1,500 ppm) was excluded from the calculations, the overall copper concentration would be 37 ppm with a standard deviation of 34 ppm and a range from 5 to 150 ppm. The data from the 207 samples were merged for the major basins and peripheral areas and summarized in Table 13. When the data were analyzed, they indicated that mean copper concentrations in the sediments of the basins of Suisun Bay, central, and south bays were significantly lower than the combined mean concentration of the peripheral areas of the south Bay (p=0.05). The mean concentration of copper in the San Pablo Bay basin was not significantly different than that of the south Bay periphery. As determined by an unpaired one-tailed T-test, the peripheral areas of San Francisco Bay, overall, had a significantly higher mean concentration of copper than the basins, overall (p=0.01). The sample with the highest concentration (1,500 ppm) of copper was taken near the ASARCO-Selby slag pile at Point Davis (Citizens for a Better Environment, 1987).

From 1971 through 1976, several dredging studies were conducted in the harbors and channels of San Francisco Bay under the auspices of the COE (COE unpublished data sheets, 1975-1979; 1979b). The number of areas sampled and the specific areas sampled varied from year to year, with a maximum of seven areas sampled in 1971 to a minimum of one area sampled in 1973, 1974, and 1976. In addition, the sampling depth varied among samples, ranging from the upper 6 inches to the upper 5 feet with the most frequent sampling depth being the upper 2.5 feet. The areas sampled during this time were: Mare Island Strait, Richmond Harbor, Richmond Harbor Channels, Oakland Outer Harbor, Alameda Naval Air Station, off Point Molate, Sausalito Channel, San Bruno Channel, Islais Creek , and Redwood City Harbor. The yearly means ranged from a low of 3.7 ppm (in 1976) to a high of 65 ppm (in 1972) (Figure 27). The lowest yearly mean was for samples taken only from the Richmond Harbor channels. The highest yearly mean was based on samples from six areas (Mare Island Strait, Richmond Harbor, off Point Molate, Oakland Outer Harbor, Alameda Naval Air Station, and Redwood City Harbor). The means for each of the six areas sampled ranged from 52 ppm in Redwood City Harbor to 84 ppm in Mare Island Strait. The samples from Mare Island Strait included seven samples with copper concentrations in excess of 100 ppm, including two with the highest concentration (117 ppm) measured at any of the dredging areas. There were only 2 years when more than one site was sampled, 1971 and 1972. In 1971, there were no significant differences between any of the sampling areas, while in 1972, Mare Island Strait was significantly different than the other five areas sampled (p=0.05).

In 1972, the United States Navy conducted a dredging study (U.S.Navy, 1972) at the Hunters Point Naval Shipyard. Based on nine samples, the mean copper concentration in the upper 6 inches of sediment was 67 ppm (Figure 27) with a standard deviation of 6 ppm. Figure 28 shows the mean copper concentrations at the areas sampled in 1972 by the COE and the Navy.

In 1973 and 1974, several intensive studies were sponsored by the COE to determine the environmental impact of dredging and dredge spoil disposal. The Pollution Distribution Study (COE, 1979b) analyzed 48 samples from three areas of San Francisco Bay in 1973: eastern San Pablo Bay and Carquinez Strait, including Mare Island Strait; San Pablo Strait/Berkeley Flats; and Oakland Inner and Outer Harbors. The overall mean concentration of copper in the upper 6 inches of sediment was 48 ppm with a standard deviation of 22 ppm and a range from 6 to 110 ppm (Figure 27). The highest single value (110 ppm) was recorded for a site between Grove Street Pier and Brooklyn Basin in Oakland Inner Harbor, the lowest value (6 ppm) was recorded for a site in the Inner Harbor Reach of Oakland Inner Harbor. When the data from the 48 individual sites were pooled into 10 subareas (smaller than those designated by the COE) and examined, the highest mean copper concentration was for five sites in Oakland Inner Harbor (69 ppm) followed by three sites off Point Richmond (65 ppm) and one site in Mare Island Strait (61 ppm). The lowest mean concentration was found at one site in Southampton Shoal (16 ppm), with the next lowest being for 18 sites at Pinole Shoals (40 ppm). There were no significant differences among the 10 sampling subareas (p=0.05).

In December 1973 and March and June 1974, Lui et al. (1975) analyzed sediment samples taken with a modified Petersen grab from seven sites around the Bay, as part of the COE's intensive dredging study. The site means for copper contamination of the sediments, based on the three sampling periods, ranged from a low of 24 ppm at the Alcatraz Disposal Site to a high of 65 ppm at the Oakland Inner Harbor site. There were no significant differences between any of the sites sampled (p=0.05).

As part of the COE's intensive dredging study, Serne and Mercer (1975) analyzed a total of 33 sediment samples from eight areas for copper concentrations during August 1973 and June 1974. The means ranged from a low of 67 ppm at Southampton Shoal to a high of 145 ppm at Islais Creek Shoals. Statistical analysis of the data indicated no significant differences between areas sampled (p=0.05).

Anderlini et al. (1975) analyzed sediment samples from 13 sites in Mare Island Strait five times from October through December 1973. In addition, they analyzed sediment samples from six of the sites four times from February through April 1974. The overall mean level of copper found in the sediments was 86 ppm with a standard deviation of 12 ppm and a range from 59 to 115 ppm. Ten of the sites were paired down the length of the strait, two were paired off the southern tip of Mare Island, and the thirteenth site was located at the disposal site off the southern end of Mare Island. When the mean copper concentrations were calculated for each pair of sites, they ranged from 94 ppm for the pair of sites midway up the strait to 71 ppm at the mouth of the strait. The three pairs of sites farthest up the strait were significantly different than the pair of sites at the mouth of the strait and the pair of sites at the tip of Mare Island (p=0.05). The disposal site (89 ppm) was also significantly different than the pair of sites at the mouth of the strait (p=0.05).

CH^2M-Hill prepared a report in 1979 for the City and County of San Francisco on the effects of untreated sewage overflows on the eastern portion of south San Francisco Bay (CH^2M-Hill, 1979). Sediments from the upper 10 to 13 cm at 23 sites between China Basin and Brisbane Lagoon were analyzed for copper. Multiple samples (two to five) were collected at each site. The overall mean concentration of copper at the 23 sites was 80 ppm with the means of the individual sites ranging from less than 36 to 293 ppm (Figure 27). The highest copper concentration (293 ppm) was found at the head of the China Basin channel, and decreased at each site from the head to the mouth of the channel; the concentration at the site at the mouth of the channel was 61 ppm. This same pattern of decreasing copper concentrations from the head to the mouth of a channel was also observed in Islais Creek, where the site at the head of the channel had a mean copper concentration of 184 ppm, while the site at the mouth had a mean of 55 ppm. The lowest copper concentration (36 ppm) was found at the site southwest of Hunters Point.

ANATEC and Kinnetic Laboratories conducted a monitoring program for the East Bay Municipal Utility District from 1980 to 1981 (Kinney & Smith, 1982). They analyzed 69 samples of the upper 10 cm of sediment from six areas (Oakland Outer Harbor, San Leandro Bay, off the Stege Plant, Berkeley Flats, Berkeley Marina, and west of Alameda Island). The overall mean copper concentration for the study was 53 ppm with a standard deviation of 19 ppm and a range of 18 to 110 ppm (Figure 27). The means for the individual sampling areas ranged from a low of 45 ppm off Alameda and on Berkeley Flats to a high of 69 ppm in San Leandro Bay. There were no significant differences between any of the sampling areas (p=0.05).

In 1981, CH2M-Hill (1981) conducted a study for the Castro Cove refinery of Chevron USA. They collected a total of 68 sediment samples from 29 sites in three areas: Castro Creek and marsh, Gallinas Creek, and Corte Madera Creek. Sampling was conducted on a quarterly basis from March through December 1983. The upper 15 cm of sediment were analyzed for copper contamination. The overall mean copper concentration for the study was 46 ppm with a standard deviation of 27 ppm and a range of from 12 to 155 ppm (Figure 27). The mean copper concentrations for the three areas were: 48 ppm for Castro Creek, 56 ppm for Gallinas Creek, and 33 ppm for Corte Madera Creek. The highest concentration (155 ppm) was found in Castro Cove. Analysis indicated that only Gallinas and Corte Madera Creeks were significantly different from each other (p=0.05).

Luoma et al. (1984) collected and analyzed 31 samples of the oxidized layer of sediment from 10 sites in Suisun Bay in 1983. The overall mean copper concentration for the study was 44 ppm with a standard deviation of 16 ppm and a range from 10 to 74 ppm (Figure 27). The means for the individual sites ranged from 10 ppm at Roe Island (two samples) to 58 ppm at Mallard Slough (four samples). The two sites with the lowest concentrations of copper, Roe Island (10 ppm) and Middle Ground (12 ppm), were significantly different than the other eight sites (p=0.05).

Spies et al. (1985b) collected and analyzed sediment samples from four sites (western San Pablo Bay, west of Berkeley, west of Oakland, and off the western end of Alameda Island) in San Francisco Bay in 1984. The overall mean for the four sites was 15 ppm, while the site means ranged from 3 ppm at the Alameda site (two samples) to 21 ppm at the San Pablo Bay site (three samples) (Figure 27).

The SBDA conducted a 5-year monitoring program from 1982 through 1986 at four sites in the southern end of south Bay (Stevenson et al., 1987). They sampled the upper 5 cm of the sediments. Two of the sites were located in the basin of south Bay, one slightly north of Dumbarton Bridge, and the other about midway between the bridge and the mouth of Coyote Creek. The other two sites were located in peripheral areas of the Bay, one in Coyote Creek and the other in Guadalupe Slough. The overall mean concentration of copper in the sediments at the four study sites over the 5-year period was 30 ppm. The overall means for the individual sites for the same period ranged from 27 to 34 ppm. There were no significant differences between any of the sites during the study period (p=0.05).

In 1986, a study on the potential environmental impact of homeporting the *U.S.S. Missouri* in San Francisco Bay was carried out for the U.S. Navy (U.S. Navy, 1986), followed by a supplemental study in 1987 (ESA, 1987). In 1986 sediment core samples were taken from four sites around the piers of Hunters Point Naval Shipyard and six sites around Treasure and Yerba Buena islands; the upper 12 inches of the cores were analyzed for copper. Two more sites at Hunters Point were sampled and analyzed in 1987. The mean copper concentration of the 12 sites was 46 ppm with a range of from 25 to 77 ppm. When the data were log-transformed and subjected to an unpaired T-test, the Hunters Point sites (34 ppm) and the Treasure Island and Yerba Buena Island sites (58 ppm) were significantly different (p=0.01).

In 1984, the Benthic Surveillance Project (BS) of NOAA's NS&T Program began analyzing samples of the upper 3 cm of sediment for heavy metal concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (NOAA, 1987a). Samples from the same sites, with the exception of the site off Oakland, were again analyzed in 1985. The overall mean copper concentration, for the 2-year period, was 38 ppm with a standard deviation of 22 ppm and a range of 9 ppm to 76 ppm. The site means ranged from 14 ppm at the Southampton Shoal site to 72 ppm at the site off Oakland (Figure 27). The single sample with the lowest copper concentration (9 ppm) was from Southampton Shoal in 1984, while the sample with the highest copper concentration (76 ppm) was from the Oakland site also in 1984. In both 1984 and 1985, samples from a site in Bodega Bay, an area minimally influenced by anthropogenic activities, were also analyzed for heavy metal concentrations. The 2-year mean for the site was 4 ppm, with a range of from below the detection limit of

0.06 ppm to 9 ppm for all three samples in 1984. The Southampton Shoal site (14 ppm) was significantly different than the Oakland (72 ppm), Hunters Point (48 ppm), and San Pablo Bay (34 ppm) sites, and the San Pablo Bay site was also significantly different than the Oakland site (p=0.05). The Bodega Bay site (4 ppm) was significantly different than all four of the San Francisco Bay sites (p=0.05).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) survey at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Chapman et al., 1986). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean copper concentration in the sediments, based on three samples per site, was 63 ppm with a range of 30 to 130 ppm (Figure 27). The Islais Creek site (99 ppm) was significantly different than the San Pablo Bay (44 ppm) and Oakland sites (46 ppm) (p=0.05).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for heavy metal concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba Buena Island, and near the San Mateo Bridge. In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987). The analyses were carried out on samples of the upper 3 cm of sediment. The overall mean copper concentration for the sites in the Bay, based on three samples per site, was 59 ppm with a range of 48 to 70 ppm (Figure 27). The individual site means ranged from 53 ppm at the San Mateo Bridge to 65 ppm at Point San Pedro; the Tomales Bay mean was 42 ppm (Figure 29). The Semple Point (63 ppm) and the Point San Pedro sites were significantly different than the Tomales Bay site, while there was no significant difference between any of the sites in the Bay (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 49 ppm, and statistical analyses indicated no significant differences between the San Francisco Bay sites, while the Bodega Bay site was significantly different than all the other sites including Tomales Bay (p=0.05). Figure 29 displays the mean concentrations from the NS&T Program data for the sites sampled in 1984 through 1986.

(2) Temporal Trends

No broad-scale, long-term monitoring of copper concentrations has been conducted in the Bay. Rather, data have been collected in various parts of the Bay in many separate studies. During the 18-year period for which data have been compiled, copper concentrations in the sediments of the Bay have fluctuated from year to year, but have displayed no long-term trends. Figure 27 compares the means by study and year to the grand mean. Despite these yearly fluctuations, no long-term trend of increasing or decreasing concentrations of mercury throughout the Bay are apparent. Because of the variability in copper concentrations from sample to sample, the yearly fluctuations may be simply due to within-site patchiness and the selection of individual stations where samples were taken each year. Some studies were performed in peripheral areas and others were conducted mainly in the basins of the Bay.

The only data set, which extended over several years at the same sites, was from the SBDA study in the southern end of the south Bay. From January 1982 through April 1986, the SBDA sampled two sites located in the south Bay basin and two sites in peripheral areas on a quarterly basis. The mean copper concentrations in the surficial sediments were at there highest (43 ppm) at the beginning of the study period, decreased to 19 ppm in January 1983, and thereafter fluctuated on a roughly annual basis with peaks in either January or April of each year (Figure 30).

When the yearly mean copper concentrations of the NOAA NS&T Program data from all the sites were compared for 1984 through 1986, 1984 and 1986 were significantly different (p=0.05). The means for the 3 years were, 40 ppm in 1984, 49 ppm in 1985, and 59 ppm in 1986. While this data appears to indicate an increasing trend in copper contamination, it should be noted that the sites sampled were different each year, and the time span involved was too short to draw any conclusions.

B. Biota

Copper levels have been measured in fish and bivalves by 17 major surveys since 1971 (Table 2). The 305 samples of mussel tissue (*Mytilus edulis; M. californianus*) analyzed for copper since 1971 show the mean concentration of copper in San Francisco Bay to have been 10.02 ppm with a median of 9.4 ppm (Table 14). Copper concentrations in mussels have ranged from 2.2 to 30.7 ppm. Median concentrations appear to better describe conditions in the basins and peripheral areas. Except for central Bay, peripheral areas adjacent to other basins produced bivalves with higher copper concentrations than the bivalves from the respective basins. Copper appears to be distributed at similar levels in San Pablo Bay, the central Bay, and the south Bay. However, since each basin is unevenly represented in the data used to calculate overall basin means, these results should be interpreted with caution. The grand median copper level in San Francisco Bay mussels sampled in 1971-1986 was elevated over those for mussels sampled at Bodega Head and in Tomales Bay by factors of approximately 1.5 to 1.2, respectively. The means and ranges in concentrations determined in individual surveys of mussels are compared with the grand mean for mussels in the Bay in Figure 31.

(1) Geographic Trends

The analysis of copper levels in Japanese littleneck clam (*Tapes semidecussata*) or soft-shell clams (*Mya arenaria*) by the U.S. EPA in 1972 (Shimmin and Tunzi, 1974) showed clams from off Albany Hills, Point Pinole, and Bayview Park near San Mateo to be the most contaminated. These clams contained more than 50 ppm copper. Clams from most other sites near Oakland, San Mateo, and Richmond had less than 20 ppm.

Anderlini et al. (1975b) sampled transplanted and resident mussels (*Mytilus edulis*) from two dredged material disposal sites and at the Berkeley pier. Copper concentrations were significantly different (lower) at the Berkeley pier (p=0.05). Many of the concentrations exceeded the grand mean for the Bay (Figure 31).

Compared to the clams analyzed by U.S. EPA in 1972, mussels (*Mytilus edulis*) and clams (*Tapes japonica*) sampled by Girvin et al. (1975) had relatively low copper concentrations (5.6 to 21.6 ppm) The highest values (21.6 ppm) were in mussels from a Redwood Creek site. The lowest (6 to 13 ppm) were in mussels from sites in the San Mateo/Foster City/Coyote Point area. Peripheral sites produced mussels with higher levels of copper than most basin sites.

In 1980, the sampling of bay mussels (*M. edulis*) from 12 sites in the Bay by California Mussel Watch (Hayes et al., 1985) and by McCleneghan et al. (1982) showed relatively low concentrations at all sites (2.2 to 10.8 ppm). The highest level of copper was detected at Coyote Point (10.8 ppm). The lowest mean copper level (2.2 ppm) was found in mussels from a Bayshore Lagoon site. Copper levels in mussels sampled by McCleneghan et al. (1982) showed no significant differences between sites (p=0.05); most were below the grand mean for the Bay (Figure 31). Sampling of Japanese littleneck clams (*T. japonica*) in 1980 by Kinney and Smith (1982) and McCleneghan et al. (1982) also showed highest copper levels (18.92 ppm) at Coyote Point (Figure 32). Clams from Foster City also contained slightly elevated copper levels (15.6 ppm). Clams (*T. japonica*) sampled by Kinney and Smith (1982) during two seasons in 1980 showed copper levels to be significantly higher at a site off Berkeley (14 ppm) compared to a site in San Leandro Bay (7.8 ppm) during August only (p=0.05). Levels of copper in *T. japonica* measured by McCleneghan et al. (1982) were significantly different at Coyote Point (18.9 ppm) as compared to five other sites in the Bay (7 to16 ppm). Clams at Point Isabel had significantly lower copper concentrations (10 ppm) than those (13.2 ppm) at a site at San Mateo (p=0.05).

Luoma et al. (1984) sampled clams (*Corbicula* sp.) in the Mendota Canal (Sacramento River) and in Suisun Bay in 1983. Concentrations of copper in clams were significantly lower in Mendota Canal as compared to four sites in Suisun Bay (p=0.05).

The NOAA NS&T Program (NOAA, 1987a) analyzed copper in the livers of starry flounder (*Platichthys stellatus*) or white croaker (*Genyonemus lineatus*) from four sites in San Francisco Bay and a site in Bodega Bay in 1984 (Figure 33). These analyses showed highest levels of copper in liver tissue of starry flounder taken from Southampton Shoal (117.8 ppm). Lowest copper levels were found in liver tissue of starry flounder from San Pablo Bay (76.1 ppm) and Bodega Bay (70.0 ppm). These concentrations were not significantly different (p=0.05). The sites and fish species sampled by the NS&T Program were apparently not sampled for copper by other investigators.

In 1985 and 1986, the California State Mussel Watch Program (Hayes and Phillips, 1986, 1987) analyzed copper in coastal mussels (*Mytilus californianus*) transplanted to 8 and 10 sites in San Francisco Bay; respectively, and in resident mussels (*M. californianus*) from Bodega Head (Figure 34). A wide range in concentrations was found among the sites (Figure 31). Highest levels of copper (10 to 30 ppm) were observed in mussels transplanted to parts of the Oakland Inner Harbor. Mussels transplanted to other peripheral areas had relatively low (less than 15 ppm) copper levels though they were higher than those transplanted to basin sites.

In 1986, the NOAA NS&T Program (Boehm et al., 1987) analyzed copper in resident mussels (*M. edulis*) from San Mateo Bridge, Dumbarton Bridge, Tomales Bay, and Bodega Head (Figure 34). Levels of copper were not different (p=0.05) among all sites (between 8 and 10 ppm). Results of sampling mussels at these sites by the NS&T Program are generally comparable to results generated by other surveys which sampled mussels nearby. At the San Mateo Bridge, Hayes et al. (1985), Hayes and Phillips (1986, 1987), and Risebrough et al. (1978) detected a mean of 9.6 ppm compared to a mean of 8.0 ppm detected by the NS&T Program. At the Dumbarton Bridge, Hayes et al. (1985), Hayes and Phillips (1986, 1987), and Risebrough et al. (1978), who sampled nearby, detected a mean of 8.8 ppm between 1976 and 1985, while the NS&T Program detected 8.6 ppm. At Bodega Head, the mean level of copper detected by Hayes et al. (1985), Hayes and Phillips (1986, 1987), and Farrington et al. (1982) between 1976 and 1986 was 6.3 ppm, while the NS&T Program detected 9.6 ppm. In Tomales Bay, Hayes et al. (1985), Hayes and Phillips (1986, 1987), Anderlini et al. (1975a), and Wyland (1975) detected a mean of 8.8 ppm between 1974 and 1982, while the NS&T Program detected 8.0 ppm in 1986.

(2) Temporal Trends

Resident mussels (*M. edulis, M. californianus*) have been resampled at four sites since 1975. Sampling at Foster City, or nearby on the San Mateo Bridge, showed copper levels have remained near 7 ppm since 1975. Sampling at Redwood Creek (and at two sites nearby) indicate a possible decline in copper levels since 1975 (from 21.6 to 8.8 ppm). Sampling at the Dumbarton Bridge showed copper levels to have remained near 7 ppm since 1980. The resampling of mussels at Bodega Head showed no significant change in copper levels since 1977 (p=0.05).

Clams (*Tapes* sp.) have been resampled in two areas of San Francisco Bay since 1972 (Shimmin and Tunzi, 1974; Girvin et al., 1975; McCleneghan et al., 1982). Sampling at Foster City showed no pattern of large changes in copper levels between 1972 and 1980. Samples taken from Albany Hill or nearby at Point Isabel showed slight declines in copper levels between 1972 and 1980 (from approximately 58 to 10.6 ppm).

Transplanted mussels (*M. californianus*) have been resampled at eight sites in San Francisco Bay since 1979 (Figure 35). No pattern of large changes in copper concentrations were apparent from these analyses at all eight sites; however, copper levels declined slightly since 1981 at the Point Pinole and Dumbarton Bridge sites and increased slightly at the Richmond Bridge site.

C. Summary

Like mercury and cadmium concentrations, copper concentrations in the sediments of San Francisco Bay and its environs display a small-scale patchiness and a large-scale homogeneity. This pattern is illustrated in Figure 27, where copper concentrations for individual samples ranged from 1 to 1,500 ppm (a difference of 1500 times), but mean concentrations for each study ranged from 4 to 131 ppm (a difference of 33 times). If the single highest and lowest samples and means were excluded, then the sample range would become 1 to 293 ppm (a difference of 293 times), while the mean range would become 15 to 95 ppm (a difference of only 6.3 times) The mean concentrations for the studies exceeded 100 ppm in only one instance (Serne and Mercer, 1975).

The means, standard deviations, medians, and ranges of copper concentrations in sediments in the four basins and selected peripheral areas based on data from all the studies compiled for this report are listed in Table 15. It also includes the number of samples taken at each area and the years in which sampling took place. While the table orders the areas from highest to lowest mean, any comparisons of areas must be done with extreme caution because of differences in sampling and analytical methodologies, time of sampling, and number of samples taken at each area. Possibly the most significant statistics in Table 15 are the ranges that show a high degree of overlap for all the areas sampled, both basins and peripheral areas. The 13 highest means are for peripheral areas, but the standard deviations are very high and the ranges in values overlap those from the four basins. The grand mean for the Bay (51 ppm, Table 12) exceeds the mean concentrations for two reference sites, Bodega Bay (4 ppm) and Tomales Bay (42 ppm) by factors of 12.75 and 1.2, respectively.

While the overall data indicate that copper concentrations in the sediments of San Francisco Bay display a small-scale patchiness and a large-scale homogeneity, the data from the individual studies indicate a pattern in which the basins of the Bay have slightly lower concentrations of copper than the peripheral areas. The existence of this pattern is supported by the1970 USGS study where the basin mean was 28 ppm and the peripheral mean was 78 ppm. Additional support comes from CH^2M-Hill's 1979 study that showed a pattern of decreasing copper concentrations moving down China Basin and Islais Creek. Many of the contaminated samples that effectively pushed the ranges in concentrations for individual studies upward in Figure 27 were attributable to sites in peripheral areas or near point sources. Those areas in which some samples were relatively highly contaminated with copper included: China Basin, Islais Creek, Oakland Inner and Outer Harbors, Redwood City Harbor, Castro Cove, and at the Selby slag site.

No long-term data exist to determine temporal trends over a broad portion of the Bay. The available data indicated yearly fluctuations in copper concentrations in sediments, but no long-term trend was apparent. An annual cycle of fluctuations appeared to occur with the SBDA study where mean copper concentrations underwent a 20 to 30 percent change within each year of the study.

The concentration of copper in bivalves appears to be very patchy. Some samples taken at any particular area may be low in copper, while other samples collected nearby or in a succeeding year may be relatively contaminated. Some of the most contaminated clam samples have been collected at sites near Albany Hills, Bayview Park, Redwood Creek, Foster City, and Coyote Point. However, other samples taken at these sites have not had high copper concentrations. Overall mean and median concentrations in mussels have been similar among the basins and are similar to analogous values from the peripheral areas. However, many of the individual samples with the most contamination were from peripheral areas. The highest individual concentrations in mussels (25 to 30 ppm) from Redwood Creek, Oakland Inner Harbor, Alameda Yacht Harbor, and south of Mare Island exceeded the grand mean for the Bay by factors of only 2.5 to 3. Mean and median concentrations in mussels from the basins of the Bay only slightly exceeded those in samples collected in 1985-86 at Bodega Head and in Tomales Bay. Small differences in copper concentrations in fish among sites have been observed.

A small data set is available to assess temporal trends in copper concentrations in biota. These limited data from monitoring the same sites in the Bay do not indicate any significant changes with time. Relatively high concentrations in mussels were observed at some dredged material disposal sites in the early 1970s and again at some peripheral sites in the mid 1980s (Figure 31). The ranges in copper concentrations among mussel sites sampled in studies from 1971 to 1986 have generally included the grand mean for the Bay, indicating that no major shifts in concentration have occurred during that period (Figure 31). Luoma et al. (1987) observed large seasonal and annual changes in copper content in *Corbicula sp.* at sites in Suisun Bay from 1983 through 1985.

Historical mean concentrations of copper in sediments sampled from 1972 through 1986 in San Francisco Bay are compared in Figure 36 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper-case print.

The NS&T Program sites iare in lower-case print. Those from the 1984 Benthic Surveillance Project are designated by "BS" after the site name; those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold, lower-case print. The overall mean for the Bay (51 ppm) did not rank particularly high compared to the NS&T Program sites. All of the basins also showed relatively low levels of copper. The mean and maximum in China Basin, however, were relatively high: The mean was exceeded only by two sites in southern California. Among the 1984 and 1986 NS&T Program sites, three in the Bay ranked in the top ten: off the Alameda NAS near Oakland, off Point San Pedro in San Pablo Bay, and off Semple Point near Vallejo. The two reference sites, Tomales Bay and Bodega Bay, ranked 19th and last (47th), respectively, among the 1984 and 1986 NS&T Program sites.

The historical mean concentrations of copper in mussels (*Mytilus edulis, M. californianus*) collected in San Francisco Bay from 1971 through 1986 are compared in Figure 37 with means from the three samples of resident mussels (*M. edulis, M. californianus*) each from the NS&T Program Pacific Coast sites sampled in 1986. The historical areas are designated in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located within the Bay are listed in bold print. The calculated, historical, grand mean for the Bay and the means for its major basins were somewhat higher than most of the concentrations seen in 1986 along the Pacific Coast. However, there was not a large range in copper concentrations among most of the San Francisco Bay and Pacific Coast sites. The maximum concentration observed in Redwood Creek was exceeded by the means from three NS&T Program sites. The two 1986 NS&T Program Mussel Watch sites in the Bay ranked 30th and 38th, respectively. The two reference sites for the Bay, Tomales Bay and Bodega Head, ranked 37th and 20th, respectively.

Table 12. Bay-wide means, standard deviations, medians, and ranges of copper concentrations in surficial sediments of San Francisco Bay based on data collected by many investigators from 1970 through 1987 from the four basins and peripheral harbors and waterways (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	51	58	46	1 - 1500	879
BASINS	36	22	30	3 - 145	376
PERIPHERY	62	73	55	1 - 1500	503

Table 13. Means, standard deviations, medians, and ranges of copper concentrations in surficial sediments of San Francisco Bay for 1970, based on USGS data (Peterson et al., 1972) (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
BASINS					
CARQUINEZ STR/SUISUN BAY	23	23	10	5 - 100	38
SAN PABLO BAY	45	27	30	5 - 100	21
CENTRAL BAY	26	20	30	5 - 70	38
SOUTH BAY	25	14	30	5 - 50	43
BASIN TOTAL	28	22	30	5 - 100	140
PERIPHERY					
CARQUINEZ STR/SUISUN BAY	48	48	50	5 - 150	13
SAN PABLO BAY	251	551	30	10 - 1500	7
CENTRAL BAY	26	17	30	10 - 50	5
SOUTH BAY	65	46	50	5 - 150	42
PERIPHERY TOTAL	78	182	50	5 - 1500	67

Table 14. Means, medians, and ranges in concentration of copper in mussels (*Mytilus edulis* or *Mytilus californianus*) collected by many investigators from the four basins and peripheral areas of San Francisco Bay, 1971-86 (ppm dw).

AREA/SITE	MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY					
BASIN	8.20	-	-	-	1
SAN PABLO BAY					
BASIN	11.33	5.69	9.65	5.3-30.7	24
PERIPHERAL-MARE ISL. ST.	14.19	4.13	14.60	8.74-19.5	6
CENTRAL BAY					
BASIN	9.23	1.92	9.20	4.9-15.0	105
PERIPHERAL-RICHMOND HBR.	11.47	3.24	10.25	9.2-16.2	4
PT. ISABEL	5.70	0.10	-	5.6-5.8	2
BERKELEY MARINA	8.53	3.00	7.05	5.1-13.2	12
ALL PERIPHERAL	8.86	3.24	8.00	5.1-16.2	18
SOUTH BAY					
BASIN	9.59	2.51	9.45	4.6-16.9	98
PERIPHERAL-ISLAIS CREEK	16.10	-	-	-	1
NEWARK SLOUGH	6.70	-	-	-	1
ALAMEDA YACHT HBR.	19.34	8.57	-	13.3-25.4	2
OAKLAND INNER	15.42	9.93	13.12	6.3-29.1	4
OAKLAND OUTER HBR	3.80	-	-	-	1
BAYSHORE LAGOON	4.22	2.80	-	2.2-6.2	2
PALO ALTO YACHT HBR.	9.40	2.14	10.10	7.0-11.1	3
REDWOOD CREEK	11.86	4.72	10.65	5.9-25.3	32
BELMONT SLOUGH	12.30	-	-	-	1
ALVISO SLOUGH	8.50	-	-	-	1
ALL PERIPHERY	11.82	5.68	10.49	2.2-29.1	47
ALL S.F. BAY	10.02	3.64	9.40	2.2-30.7	305
TOMALES BAY	9.36	4.36	7.75	3.8-22.3	28
BODEGA HEAD	6.51	2.23	6.10	2.1-13.7	53

Table 15. Means, standard deviations, medians, and ranges of copper concentrations in the surficial sediments of San Francisco Bay for the four basins and selected peripheral areas based on data collected by many investigators from 1970 through 1987, ordered from highest to lowest by mean (ppm dw).

AREA	YEARS SAMPLED	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
CHINA BASIN	79	150	108	122	61 - 293	4
MARE ISLAND STRAIT	70-74	83	16	62	44 - 128	124
ISLAIS CREEK	70, 71, 79, 85	78	54	70	9 - 184	12
OAKLAND INNER HARBOR	73, 74	72	45	79	6 - 166	14
SAN LEANDRO BAY	80-81	69	25	76	22 - 110	15
REDWOOD CITY HARBOR	71-74	66	41	56	19 - 173	18
HUNTERS POINT NS	72-74, 86, 87	61	10	62	42 - 78	20
OAKLAND OUTER HARBOR	72-74, 80, 81	58	26	55	14 - 159	29
GALLINAS CREEK	81	56	25	45	22 - 120	19
ALAMEDA NAS	71-73	54	12	54	22 - 79	25
BERKELEY MARINA	80-81	50	10	52	31 - 70	15
CASTRO COVE	81	48	32	44	12 - 155	30
POINT MOLATE	71, 72	47	5	47	37 - 58	10
SAN PABLO BAY	70, 73, 84-86	45	24	41	5 - 131	58
CARQUINEZ STRAIT/SUISUN BAY	70, 73, 74, 83	39	24	39	5 - 100	78
RICHMOND HARBOR	72-74, 76	36	29	30	1 - 136	48
COYOTE CREEK	82-86	34	9	36	19 - 54	20
CENTRAL BAY	70, 71, 73, 74, 80, 81, 84-86	33	20	30	5 - 86	114
CORTE MADERA	81	33	13	31	14 - 56	19
SOUTH BAY	70, 71, 73, 74, 79, 80, 82-86	33	17	30	3 - 76	124
GUADALUPE SLOUGH	82-86	30	8	32	14 - 39	20
BODEGA BAY	84-85	4	4	3	<.06 - 9	6
TOMALES BAY	86	42	2	42	40 - 43	3

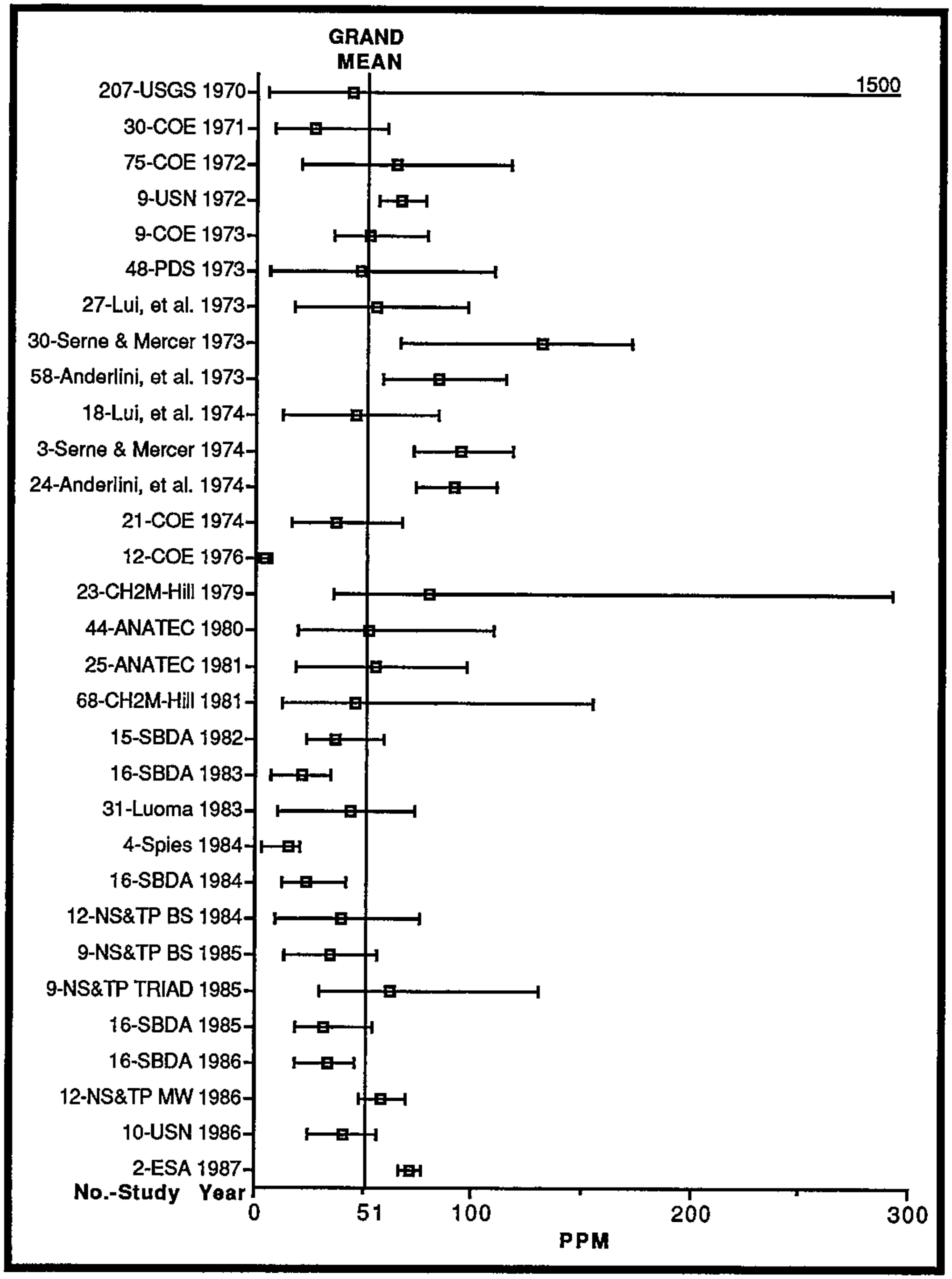


Figure 27. Mean concentration of copper in the surficial sediments of San Francisco Bay by study and year compared to the grand mean for the Bay (ppm dw) (No.=number of samples, bars represent the range).

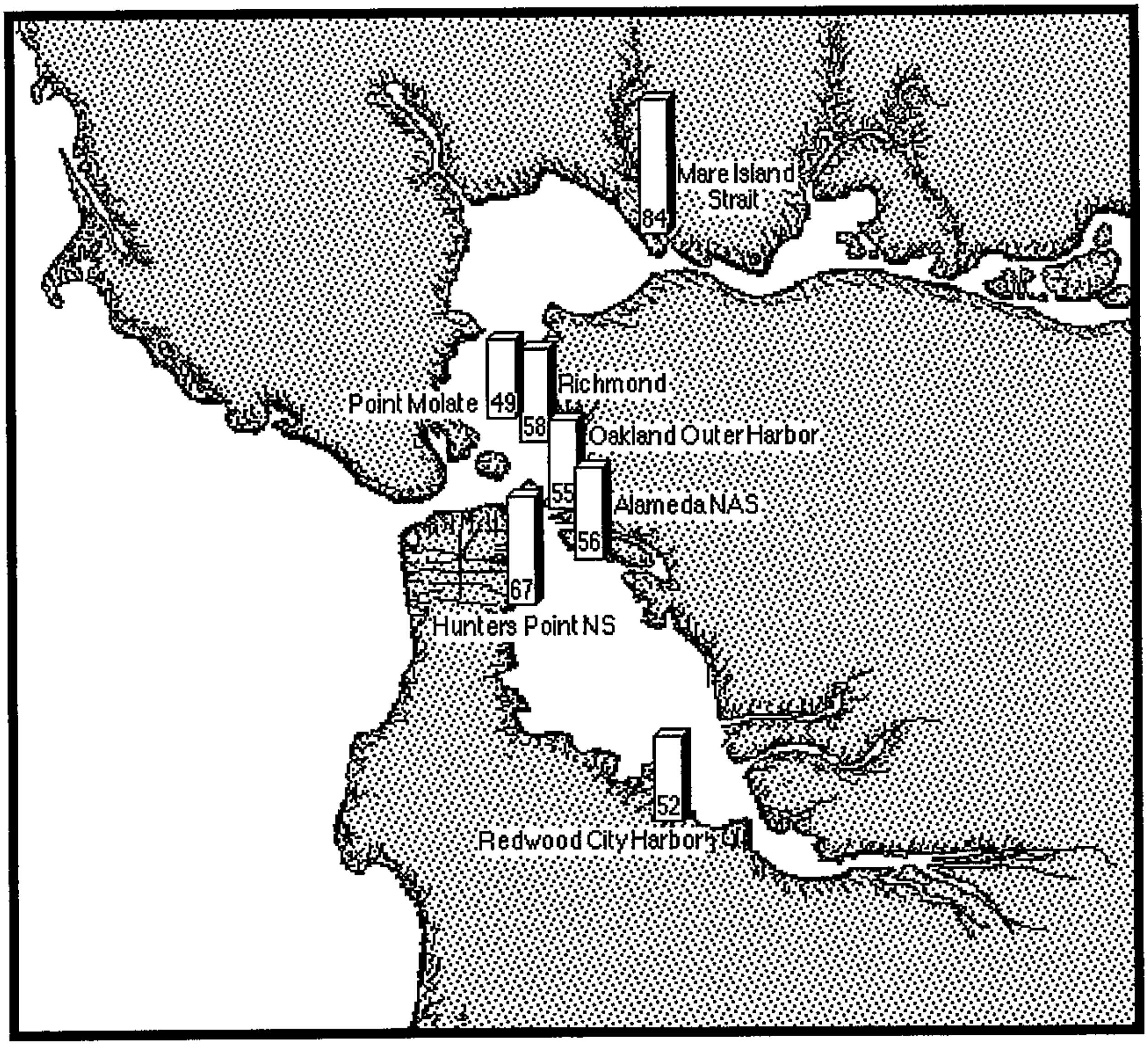


Figure 28. Mean copper concentrations, in ppm dw, based on 1972 COE and US Navy dredging studies (COE, 1979a; U.S. Navy, 1972).

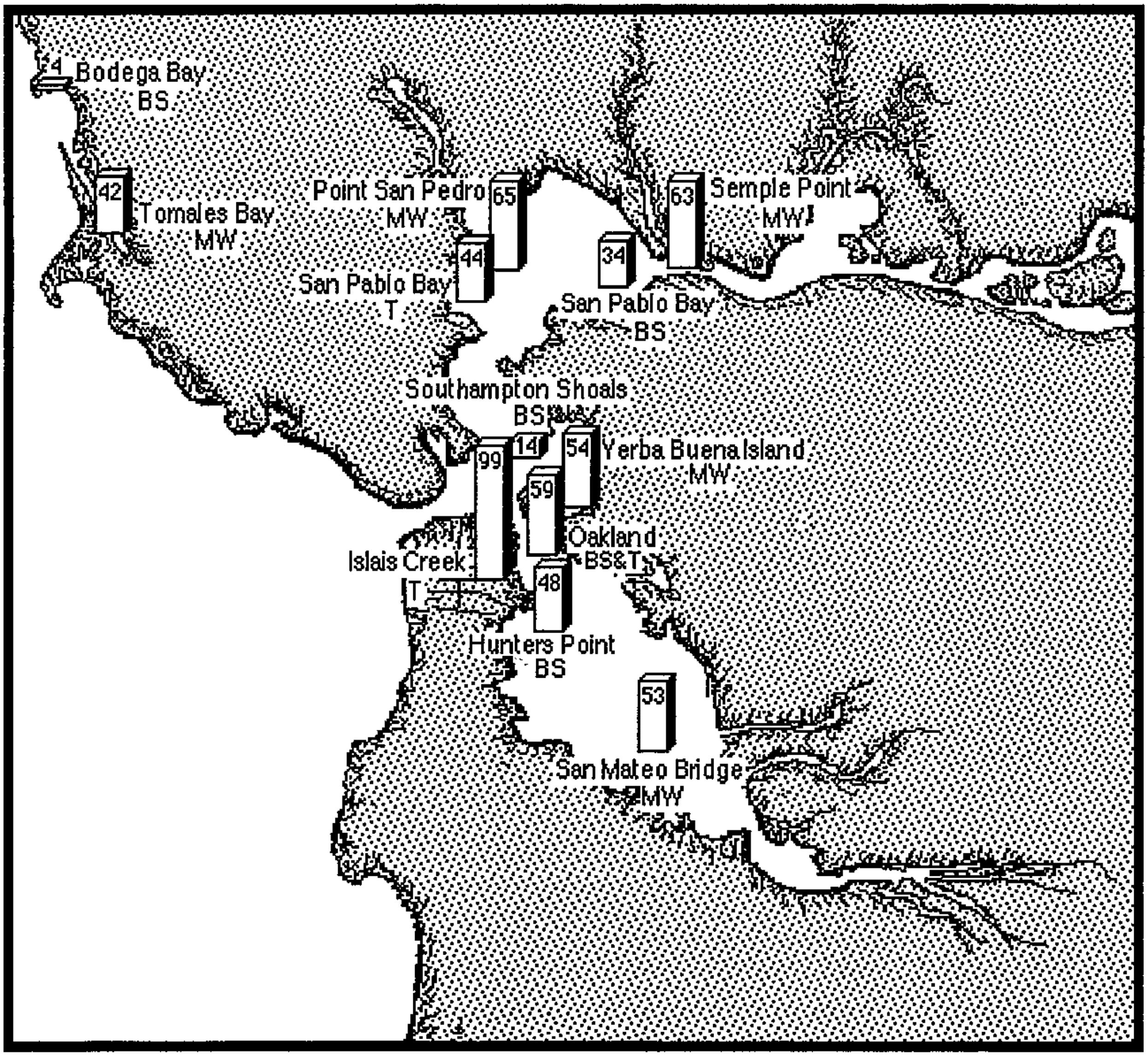


Figure 29. Mean copper concentrations in the surficial sediments for 1984-86, in ppm dw, based on NOAA NS&T Program data (BS=Benthic Surveillance, MW=Mussel Watch, and T=Sediment Quality Triad study) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986) .

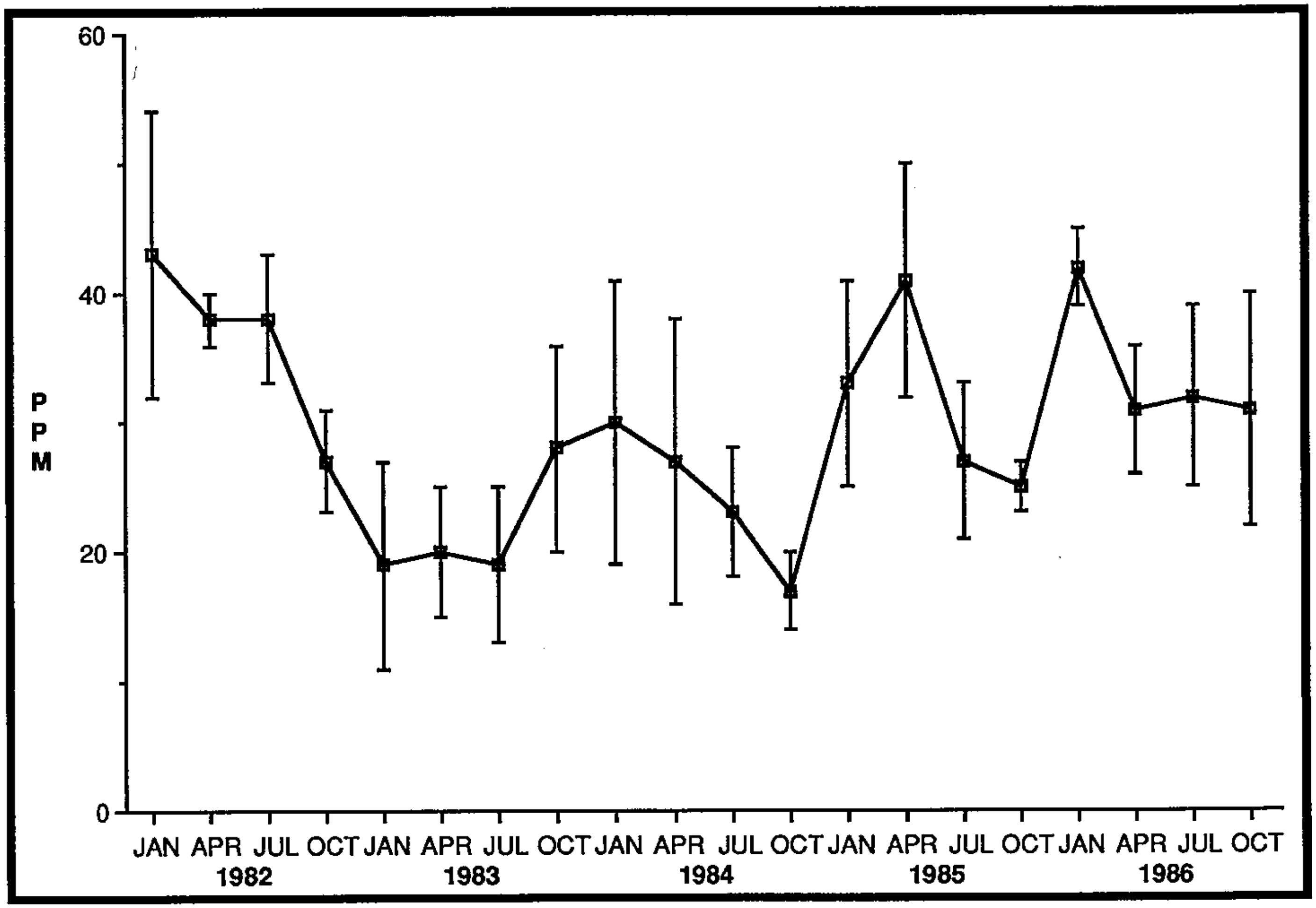


Figure 30. Monthly mean copper concentration in the surficial sediments at the four sites in the southern end of south Bay sampled by the SBDA from 1982 through 1986 (bars represent one standard deviation) (Stevenson et al., 1987).

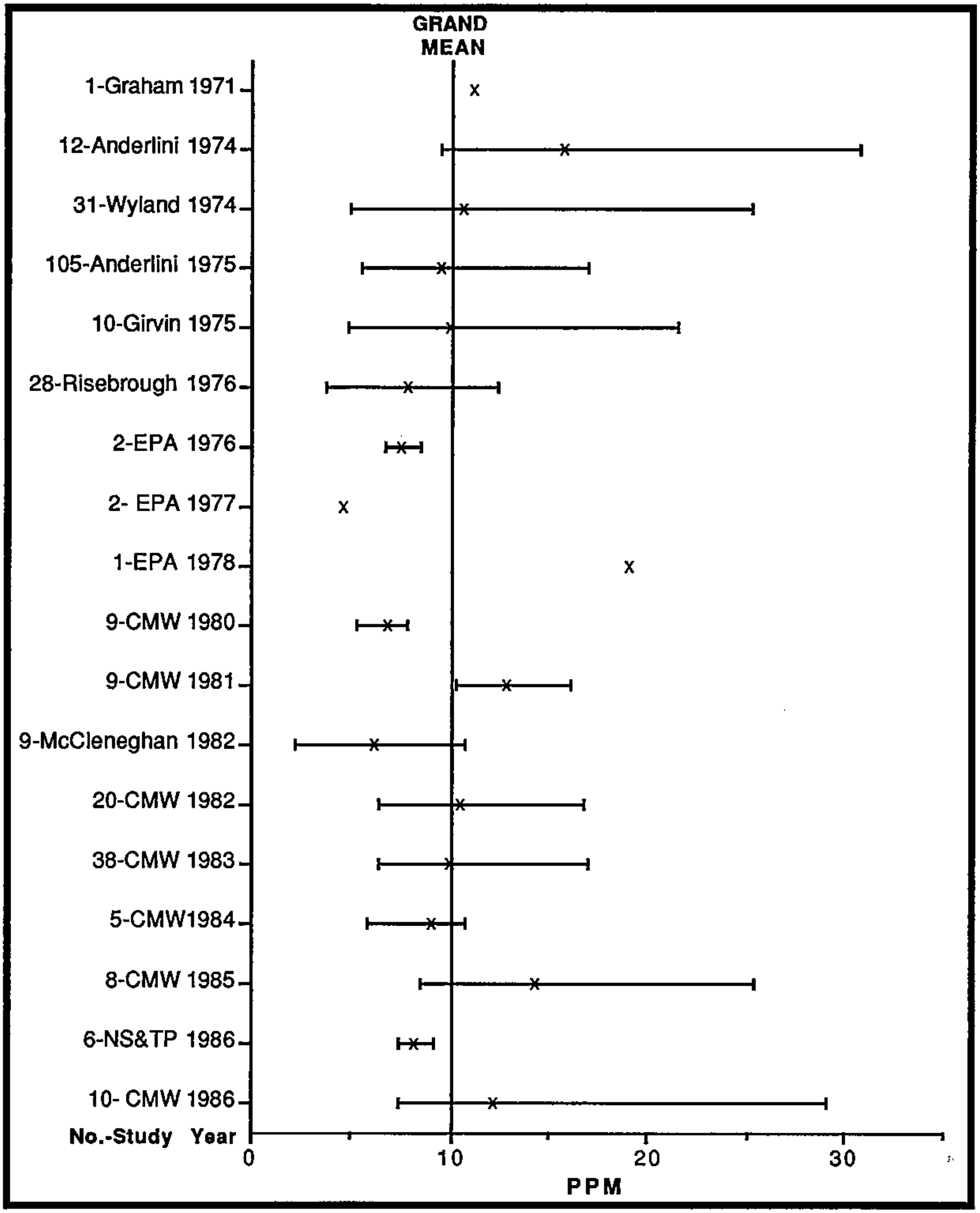


Figure 31. Mean concentration of copper in mussels (Mytilus edulis or M. californianus) by study and year in ppm dw (No.=number of samples, bars represent the range).

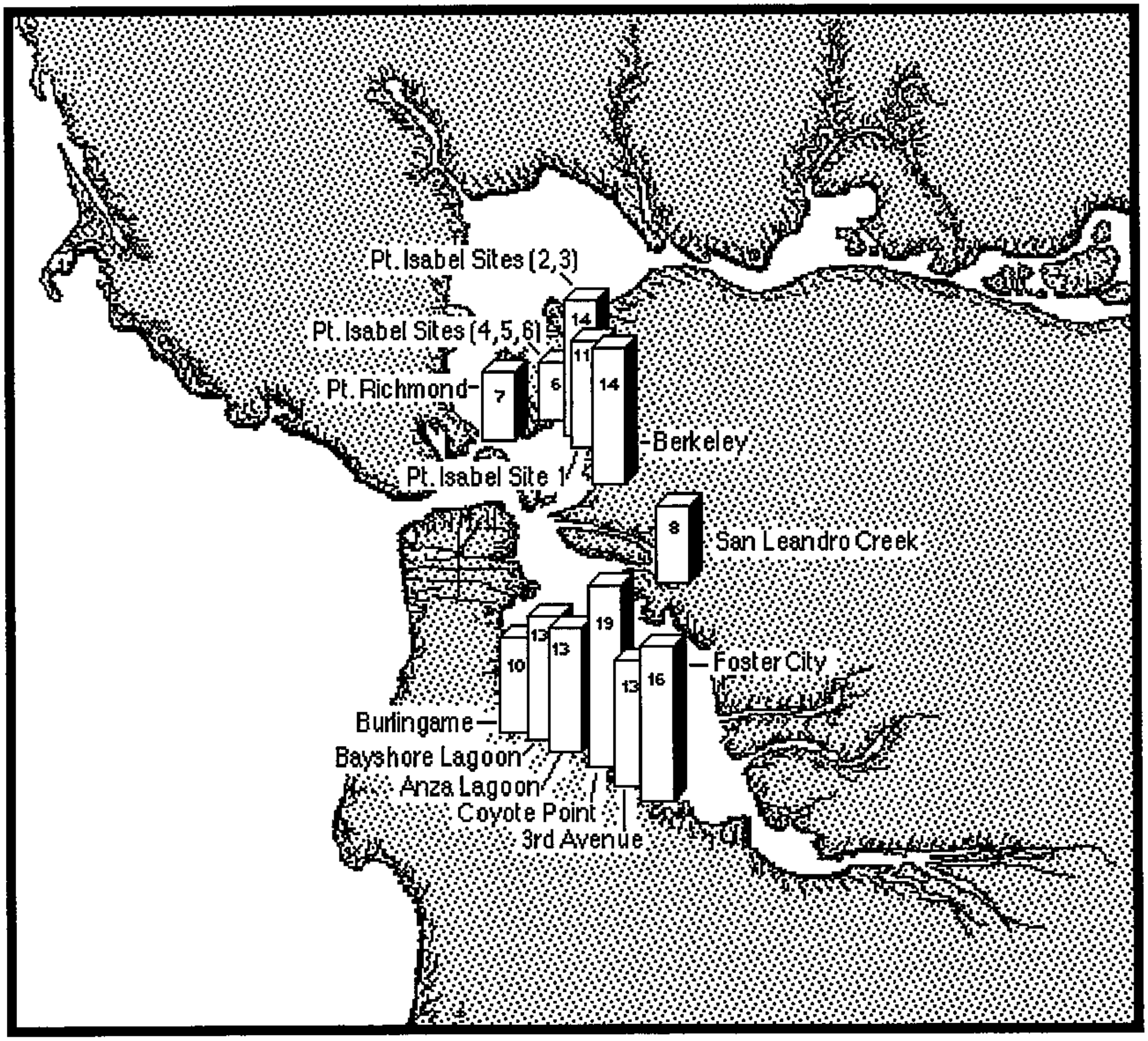


Figure 32. Copper concentrations in Japanese littleneck clams (Tapes japonica) in 1980 (ppm dw) (McCleneghan et al., 1982; Kinney and Smith, 1982).

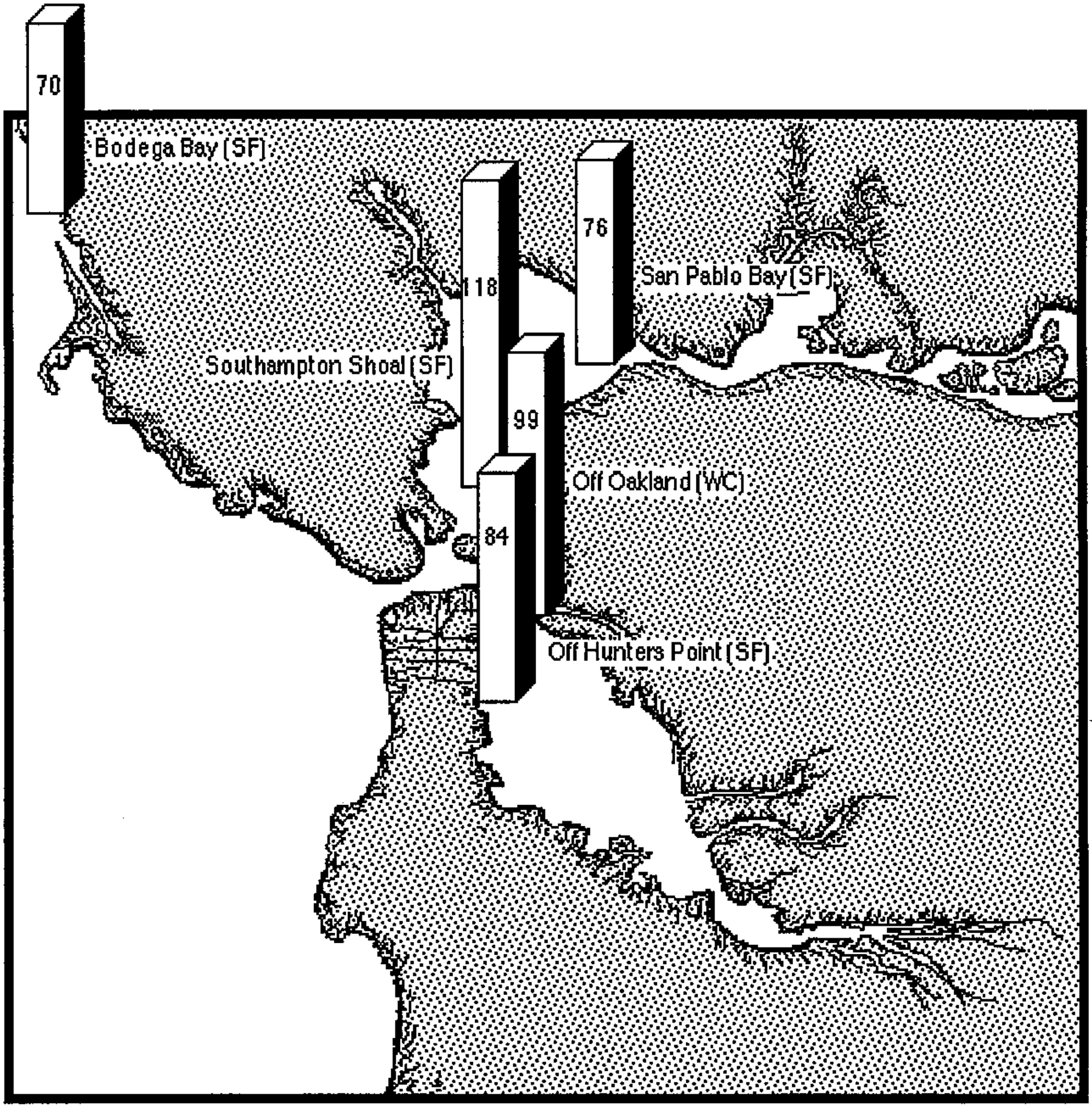


Figure 33. Copper in liver tissue of starry flounder (SF), Platichthys stellatus, and white croaker (WC), Genyonemus lineatus, sampled in 1984 (ppm dw)(NOAA, 1987a).

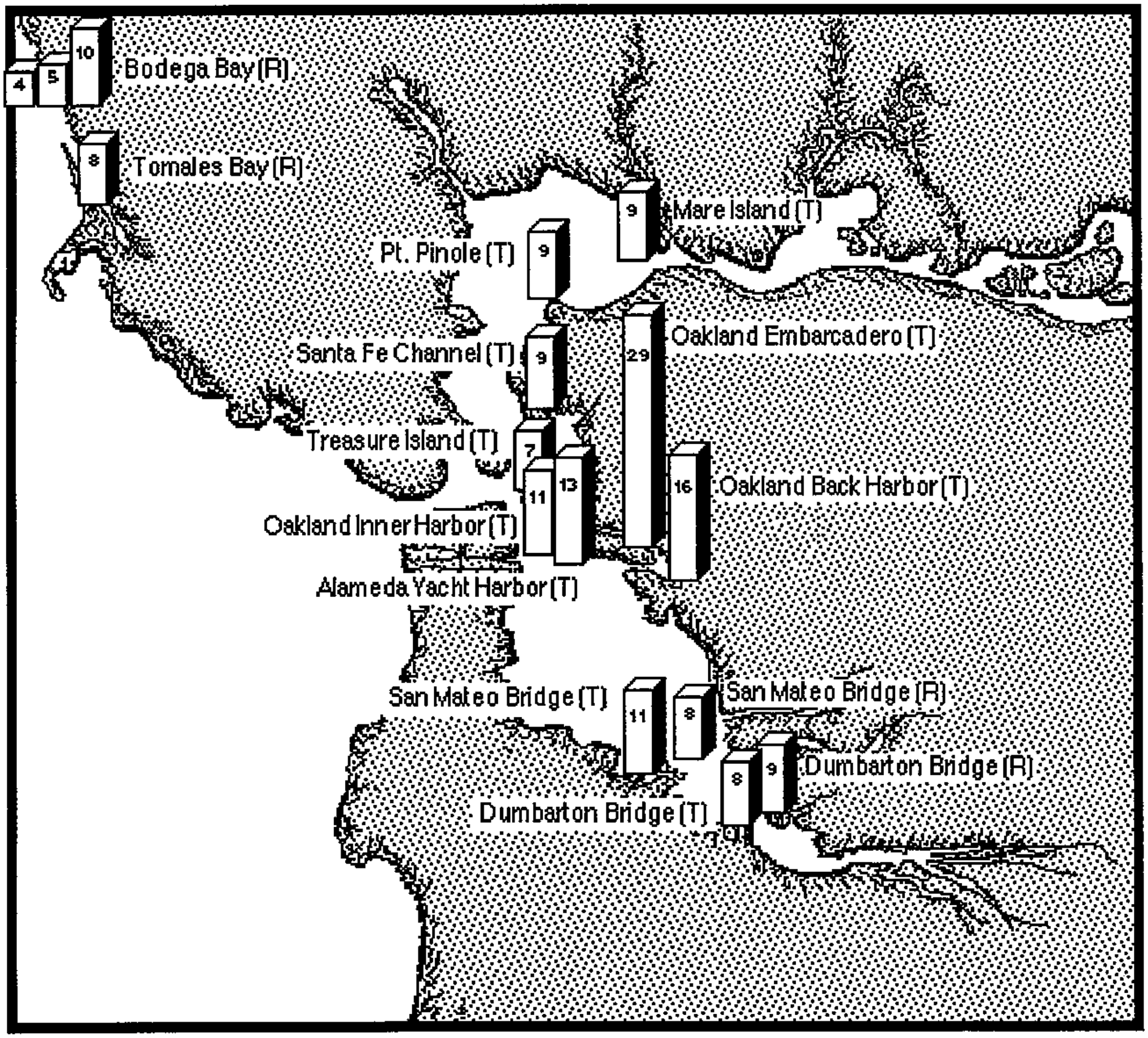


Figure 34. Copper in transplanted (T) coastal mussels (Mytilus californianus) and resident (R) bay mussels (M. edulis) sampled in 1985-86 by CMW and NS&T Program (Hayes and Phillips, 1987; Boehm et al., 1987).

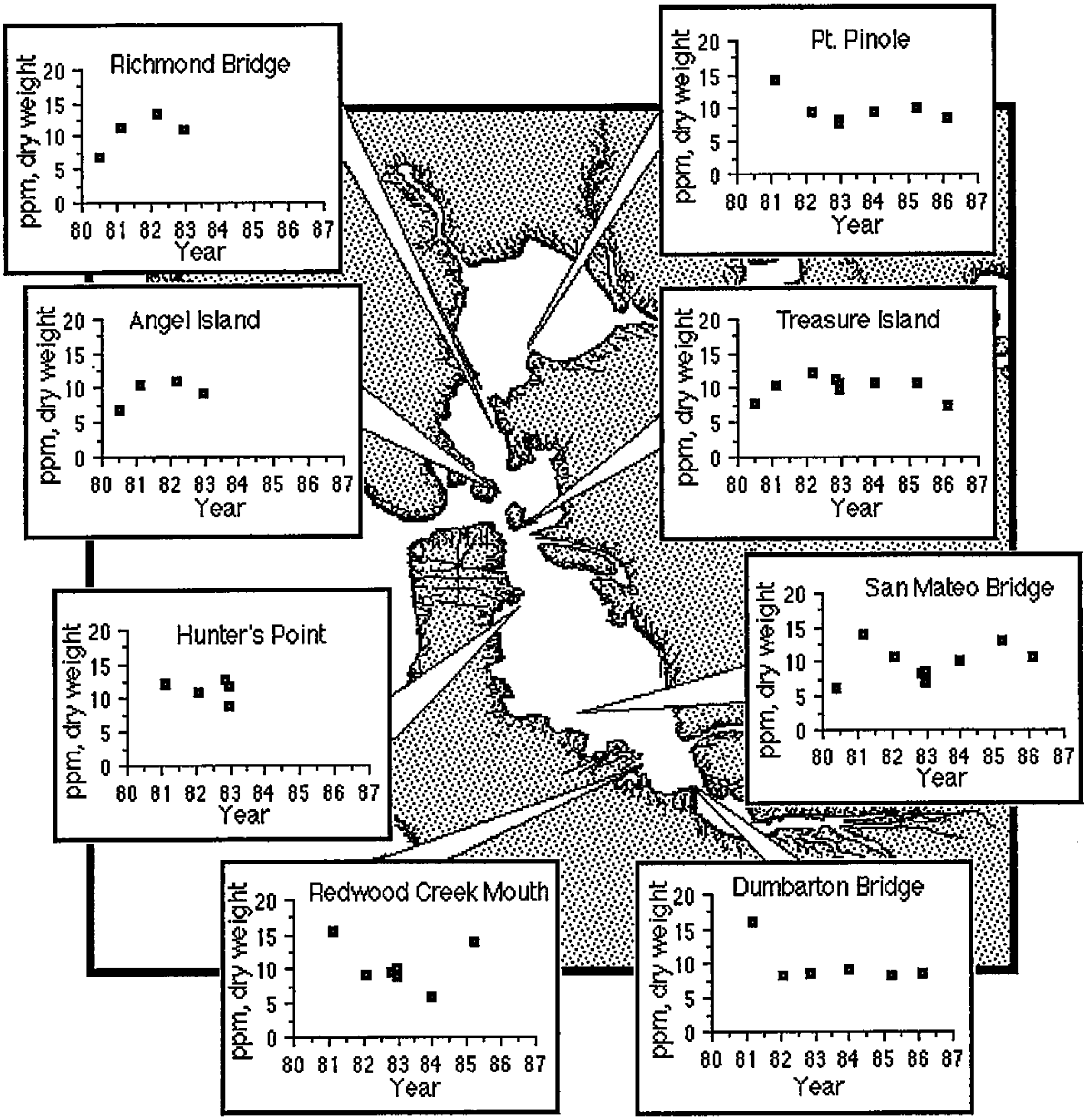


Figure 35. Temporal trends in copper concentrations in transplanted mussels (Mytilus californianus), 1980-86 (Hayes et al., 1985; Hayes and Phillips, 1986, 1987).

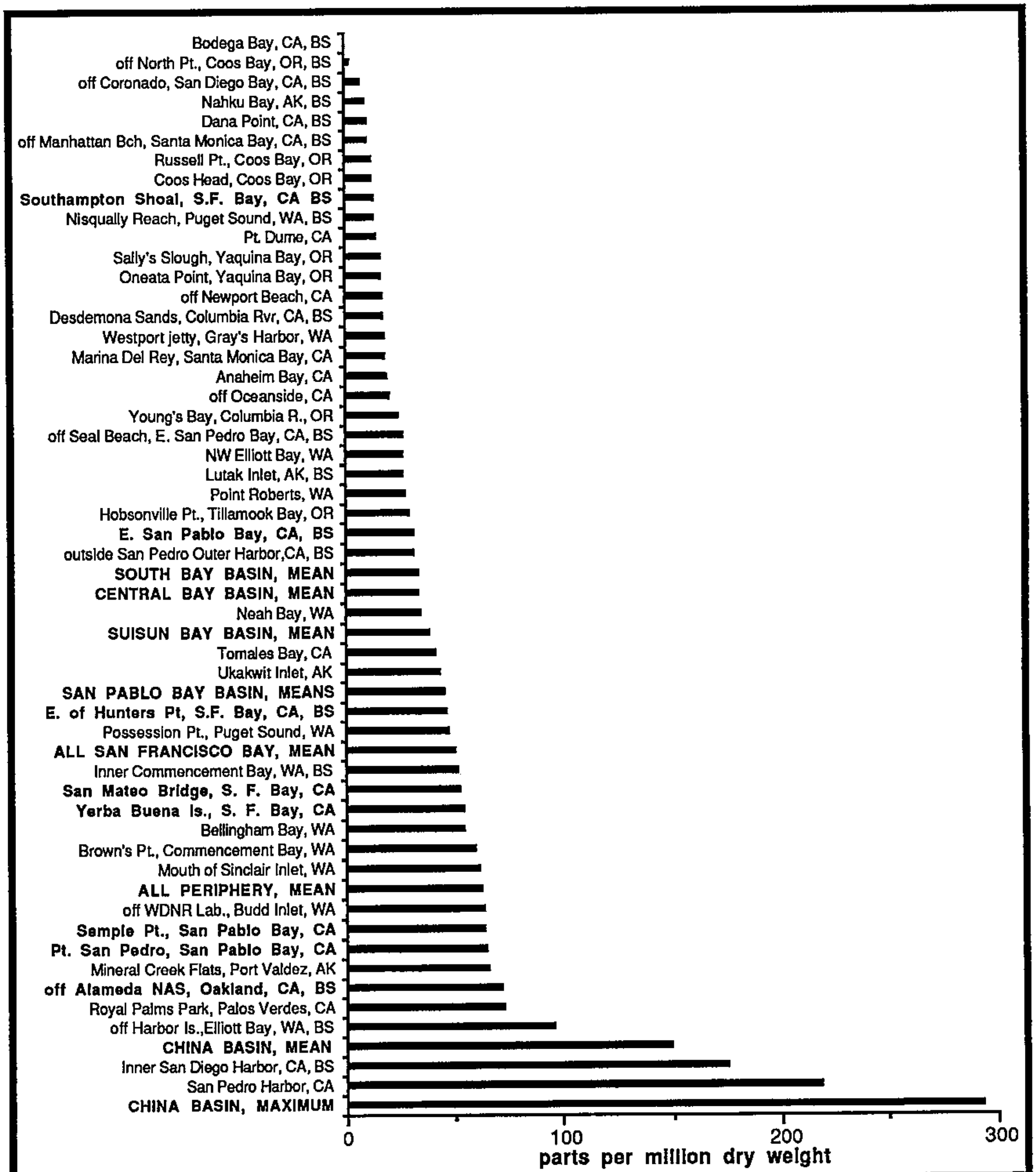


Figure 36. Comparison of copper concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Tables 12, 15), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name.

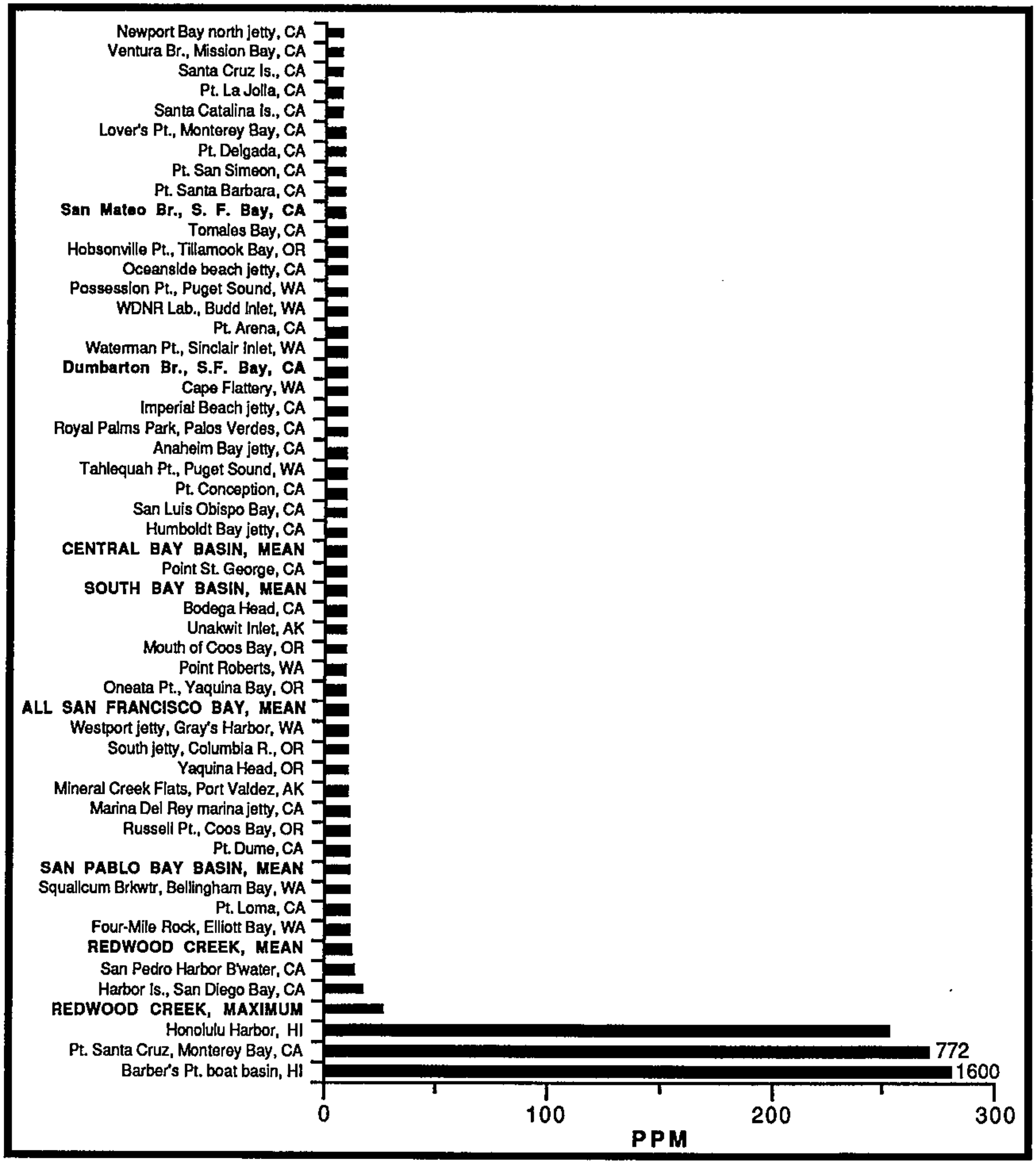


Figure 37. Mean copper concentrations in resident mussels (*Mytilus edulis, M. californianus*) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1971-1986) data for San Francisco Bay (from Table 14). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

6

GEOGRAPHIC AND TEMPORAL TRENDS IN LEAD CONTAMINATION

A. Sediments

Data have been compiled by numerous investigators on the concentration of lead in the surface sediments of San Francisco Bay and its environs for the years 1970 through 1987. Based on more than 1,300 samples collected throughout the system, the grand mean concentration of lead in San Francisco Bay sediments for the last 18 years was 56 ppm with a standard deviation of 300 ppm and a range of from 1 to 10,000 ppm (Table 16). The vast majority of the lead values (88 percent) were between 10 and 100 ppm inclusive; 7 percent were less than 10 ppm, while 4 percent were greater than 100 ppm (three samples were in excess of 1,000 ppm). The median value was 38 ppm. If the single sample with the highest lead concentration (10,000 ppm) was excluded from the calculations, the grand mean for lead would be 49 ppm, a reduction of 12.5 percent, with a standard deviation of 120 ppm and a range of 1 to 3,000 ppm. The median would remain unchanged. The means and ranges in concentrations for individual surveys are summarized in Figure 38 and compared to the grand mean for the Bay.

(1) Geographic Trends

The most thorough study of lead contamination in San Francisco Bay was conducted by the USGS in 1970 (Peterson et al., 1972). The USGS analyzed 206 samples of the upper 6 inches of sediment from throughout the Bay area for copper and other metals. They found an overall mean copper concentration of 107 ppm with a standard deviation of 727 ppm and a range of from 5 to 10,000 ppm (Figure 38). If the single sample containing the highest concentration of lead (10,000 ppm) was excluded from the calculations the overall lead concentration would be 59 ppm (a reduction of 45 percent) with a standard deviation of 221 ppm and a range of from 5 to 3,000 ppm. Exclusion of the two highest lead concentrations (3,000 and 10,000 ppm) from the calculations would reduce the mean by a total of 63 percent to 40 ppm with a standard deviation of 46 ppm and a range of 5 to 500 ppm. In all three cases, the median lead concentration was 30 ppm. The data from the 206 samples were merged for the major basins and peripheral areas and summarized in Table 17. Analysis of the data indicated that the basins of Suisun Bay, central, and south bays were significantly different than the combined mean concentration of the peripheral areas of the south Bay ($p=0.05$). As determined by an unpaired one-tailed T-test, the peripheral areas (279 ppm) of San Francisco Bay were significantly different than the basins (30 ppm) ($p=0.01$). The sample with the highest concentration of lead (10,000 ppm) was taken from an ASARCO-Selby slag site, near Point Davis (Citizens for a Better Environment, 1987), and the second highest concentration of lead (3,000 ppm) was measured in a sample from the southern end of the Alameda estuary.

From 1971 through 1979, numerous dredging studies were conducted in the harbors and channels of San Francisco Bay under the auspices of the COE (COE unpublished data sheets,1975-1979 ; 1979b). The number of areas sampled and the specific areas sampled varied among years from a maximum of 14 areas sampled in 1971 to a minimum of 4 areas sampled in 1977 and 1979. In addition, the sampling depth varied from sample to sample, ranging from the upper 6 inches to the upper 5 feet with the most frequent sampling depth being the upper 2.5 feet. The areas most consistently sampled were Mare Island Strait, Richmond Harbor Channels, Oakland Inner and Outer Harbors, and Alameda Naval Air Station. The yearly means ranged from a low of 29 ppm in 1975 to a high of 56 ppm in 1972 with five of the nine values falling between 40 ppm and 48 ppm (Figure 38). The overall mean lead concentration for the 9 years was 43 ppm with a range from 1 to 286 ppm.

There were no significant differences among areas sampled in 3 of the 9 years (1977, 1978, and 1979) ($p=0.05$) as shown in Table 18. The ranking of sites varied from year to year with no clear patterns appearing (Table 18). The sites that were significantly different from each other also varied from year to year. The COE dredging data indicated that lead was ubiquitous in the sediments of the channels sampled in San Francisco Bay.

In 1972, the United States Navy conducted a dredging study (U.S. Navy, 1972) at the Hunters Point Naval Shipyard. Based on nine samples, the mean lead concentration in the upper 6 inches of sediment was 57 ppm, with a range of 47 to 70 ppm (Figure 38) and standard deviation of 8 ppm. Figure 39 shows the mean lead concentrations at the areas sampled in 1972 by the COE and the Navy.

In 1973 and 1974, several intensive studies were sponsored by the COE to determine the environmental impact of dredging and dredge spoil disposal. The Pollution Distribution Study (COE, 1979b) analyzed 48 samples from three areas of San Francisco Bay in 1973: eastern San Pablo Bay and Carquinez Strait, including Mare Island Strait; San Pablo Strait/Berkeley Flats; and Oakland Inner and Outer Harbors. The overall mean concentration of lead in the upper 6 inches of sediment was 58 ppm with a standard deviation of 71 ppm and a range from 6 to 421 ppm (Figure 38). The highest single value (421 ppm) was recorded for a site at the mouth of Mare Island Strait, the lowest value (6 ppm) was recorded for a site in the Inner Harbor Reach of Oakland Inner Harbor. When the data from the 48 individual sites were pooled into 10 subareas (smaller than those designated by the COE) and examined, the highest mean lead concentration was for 5 sites in Oakland Inner Harbor (131 ppm) followed by 18 sites at Pinole Shoals (59 ppm). The lowest mean concentration was found at one site, Southampton Shoals (13 ppm), with the next lowest being for the six sites between Richmond and San Rafael (36 ppm). There were no significant differences among the 10 sampling subareas ($p=0.05$).

In December 1973 and again in March and June, 1974 Lui et al. (1975) analyzed sediment samples taken with a modified Petersen grab from seven sites around the Bay as part of the COE's intensive dredging study. The site means for lead contamination of the sediments, based on the three sampling periods, ranged from a low of 28 ppm at the South Bay Disposal Site to a high of 63 ppm at the Oakland Inner Harbor site. The Oakland Inner Harbor was found to be significantly different than the three sites with the lowest lead concentrations: the South Bay Disposal Site, Mare Island Strait site (29 ppm), and Alcatraz Disposal Site (30 ppm) ($p=0.05$).

As part of the COE's intensive dredge study, Serne and Mercer (1975) analyzed a total of 33 sediment samples from eight areas for lead concentrations during August 1973 and June 1974. The means ranged from a low of 10 ppm at Southampton Shoals to a high of 96 ppm in Oakland Inner Harbor. Statistical analysis of the data indicated that only the highest and lowest sites were significantly different from each other ($p=0.05$).

Anderlini et al. (1975) analyzed sediment samples from 13 sites in Mare Island Strait five times from October through December 1973. In addition, they analyzed sediment samples from six of the sites four times from February through April 1974. The overall mean level of lead found in the sediments was 49 ppm with a standard deviation of 11 ppm and a range from 29 to 84 ppm. Ten of the sites were paired down the length of the strait, two were paired off the southern tip of Mare Island, and the thirteenth site was located at the disposal site off the southern end of Mare Island. When the mean lead concentrations were calculated for each pair of sites, they ranged from 43 ppm for the pair of sites just above the mouth of the strait to 57 ppm at the pair of sites midway up the strait. There were no significant differences between any of the pairs of sites ($p=0.05$).

CH^2M-Hill prepared a report in 1979 for the City and County of San Francisco on the effects of untreated sewage overflows on the eastern portion of south San Francisco Bay (CH^2M-Hill, 1979). Sediments from the upper 10 to 13 cm at 23 sites between China Basin and Brisbane Lagoon were analyzed for lead. Multiple samples (two to five) were collected at each site. The overall mean concentration of lead at the 23 sites was 241 ppm with the means of the individual sites ranging from 30 to 2,580 ppm (Figure 38). The highest mean lead concentration (2,580 ppm) was found at the head of the China Basin channel. The concentrations decreased at each of the other three sites (678, 103, and 48 ppm) from the head to the mouth of the channel. This same pattern of decreasing lead concentrations from the head to the mouth of a channel was also observed in Islais Creek, where the site at the head of the channel had a mean lead concentration of 882 ppm, while the site at the mouth had a mean of 49 ppm. The lowest mean lead concentration (30 ppm) found in the survey was found at a site just east of Hunters Point.

ANATEC and Kinnetic Laboratories conducted a monitoring program for the East Bay Municipal Utility District from 1980 to 1981 (Kinney and Smith, 1982). They analyzed 69 samples of the upper 10 cm of sediment from six areas (Oakland Outer Harbor, San Leandro Bay, off the Stege Plant, Berkeley Flats, Berkeley Marina, and west of Alameda Island). The overall mean lead concentration for the study was 78 ppm with a standard deviation of 51 ppm and a range of 20 to 280 ppm (Figure 38). The means for the individ- ual sampling areas ranged from a low of 36 ppm on the Berkeley Flats, to a high of 126 ppm in San Leandro Bay. The San Leandro Bay area was found to be significantly different than the three areas with the lowest mean lead concentrations: Berkeley Flats, Alameda Island (40 ppm), and Oakland Outer Harbor (45 ppm) (p=0.05).

In 1981, CH2M-Hill (1981) conducted a study for the Castro Cove refinery of Chevron USA. They collected a total of 94 sediment samples from 29 sites in three areas: Castro Creek and marsh, Gallinas Creek, and Corte Madera Creek. Sampling was conducted on a quarterly basis from March through December 1983. The upper 15 cm of sediment were analyzed for lead contamination. The overall mean lead concentration for the study was 21 ppm with a standard deviation of 16 ppm and a range of from 2 to 77 ppm (Figure 38). The mean lead concentrations for the three areas were: 26 ppm for Castro Creek, 21 ppm for Gallinas Creek, and 13 ppm for Corte Madera Creek. Analysis indicated that only Castro and Corte Madera Creeks were significantly different from each other (p=0.05).

Luoma et al. (1984) collected and analyzed 31 samples of the oxidized layer of sediment from 10 sites in Suisun Bay. The overall mean lead concentration for the study was 36 ppm with a standard deviation of 11 ppm and a range from 13 to 59 ppm (Figure 38). The means for the indiviual sites ranged from 17 ppm at Roe Island (two samples) to 48 ppm at New York Slough (five samples). The two sites with the lowest concentrations of lead, Roe Island and Middle Ground (18 ppm), were significantly different than the site with the highest lead concentration, New York Slough (p=0.05).

Spies et al. (1985b) collected and analyzed sediment samples from four sites (western San Pablo Bay, west of Berkeley, west of Oakland, and off the western end of Alameda Island) in San Francisco Bay in 1984. The overall mean for the four sites was 19 ppm, while the site means ranged from 8 ppm at the Alameda site (two samples) to 27 ppm at the Oakland site (three samples).

The SBDA conducted a 5-year monitoring program from 1982 through 1986 at four sites in the southern end of south Bay (Stephenson et al., 1987). They sampled the upper 5 cm of the sediments. Two of the sites were located in the basin of the south Bay, one slightly north of Dumbarton Bridge and the other about midway between the bridge and the mouth of Coyote Creek. The other two sites were located in peripheral areas of the Bay, one in Coyote Creek and the other in Guadalupe Slough. The overall mean concentration of lead in the sediments at the four study sites over the 5-year period was 29 ppm. The overall means for the individual sites for the same period ranged from 21 to 34 ppm. The site north of Dumbarton Bridge (21 ppm) was found to be significantly different than the Coyote Creek (32 ppm) and Guadalupe Slough (34 ppm) sites (p=0.05).

In 1986, a study on the potential environmental impact of homeporting the *U.S.S. Missouri* in San Francisco Bay was carried out for the U.S. Navy (U.S. Navy, 1987), followed by a supplemental study in 1987 (ESA, 1987). In 1986, sediment core samples were taken from four sites around the piers of Hunters Point Naval Shipyard and six sites around Treasure Island and Yerba Buena Island; the upper 12 inches of the cores were analyzed for lead. Two more sites at Hunters Point were sampled and analyzed in 1987. The mean lead concentration at the 12 sites was 26 ppm with a range from 8 to 53 ppm. When the data were log-transformed and subjected to an unpaired T-test, there was no significant difference between the two areas sampled.

In 1984, the Benthic Surveillance Project (BS) of NOAA's NS&T Program began analyzing samples of the upper 3 cm of sediment for heavy metal concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (NOAA, 1987a). Samples from the same sites, with the exception of the site off Oakland, were again analyzed in 1985. The overall mean lead concentration for the 2-year period was 15 ppm with a standard deviation of 14 ppm and a range of 3 ppm to 46 ppm. The site means ranged from 5 ppm at the

Southampton Shoal site to 44 ppm at the site off Oakland (Figure 40). The single samples with the lowest lead concentration (3 ppm) were from Southampton Shoal in 1985 and Hunters Point in 1984, while the sample with the highest lead concentration (46 ppm) was from the Oakland site in 1984. In both 1984 and 1985, samples from a site in Bodega Bay, an area minimally influenced by anthropogenic activities, were also analyzed for heavy metal concentrations. The 2-year mean for the site was 1 ppm, with a range of from below the detection limit of 0.2 ppm for all three samples in 1984 to 3 ppm. The Oakland site was significantly different than the other three sites, and the Southampton Shoal and Hunters Point (17 ppm) sites were significantly different from each other (p=0.05). The Bodega Bay site (1 ppm) was significantly different than all four of the San Francisco Bay sites (p=0.05).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) survey at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Chapman et al., 1986). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean lead concentration in the sediments, based on three samples per site, was 60 ppm with a range of 18 to 223 ppm (Figure 38). The Islais Creek site (129 ppm) was significantly different than the San Pablo Bay (21 ppm) and Oakland sites (31 ppm) (p=0.05).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for heavy metal concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba Buena Island, and near the San Mateo Bridge (Figure 40). In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987). The analyses were carried out on the upper 1 cm of sediment. The overall mean lead concentration for the sites in the Bay, based on three samples per site, was 30 ppm with a range of 20 to 39 ppm (Figure 38). The individual site means ranged from 23 ppm at Semple Point to 38 ppm at Yerba Buena Island; the Tomales Bay mean was 20 ppm (Figure 40). The Semple Point and the Point San Pedro (28 ppm) sites were significantly different than the Yerba Buena site, and the Semple Point and San Mateo Bridge (31 ppm) sites were significantly different from each other (p=0.05). The Tomales Bay site was found to be significantly different than all the Bay sites except for Semple Point (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 29 ppm, and statistical analysis indicated no significant differences between seven of the San Francisco Bay sites; the site with the lowest lead concentration (Southampton Shoal, 5 ppm) was significantly different than all the Bay sites except for east San Pablo Bay (8 ppm). The east San Pablo Bay site was significantly different than the five most contaminated sites, and the most contaminated site (Islais Creek, 129 ppm) was significantly different than the five least contaminated sites (p=0.05). The Bodega Bay site (1 ppm) was significantly different than all the other sites including the Tomales Bay site, while the Tomales Bay site was not significantly different than any of the San Francisco Bay sites. Figure 40 graphically displays the mean concentrations from the NS&T Program (BS, Triad, MW) data for the sites sampled in 1984 through 1986.

(2) Temporal Trends

During the 18-year period for which data have been compiled, lead concentrations in the sediments of the Bay have fluctuated from year to year but have displayed no long-term trends. Figure 38 compares the means by study and year to the grand mean. Despite these yearly fluctuations, no long-term trend of increasing or decreasing concentrations of lead throughout the Bay are apparent. Because of the high variability in lead concentrations from sample to sample, the yearly fluctuations may be simply due to within-site patchiness and the selection of individual stations where samples were taken each year.

Figure 41 indicates that mean concentrations for five harbor areas fluctuated yearly over a 9-year period, but with no apparent long-term trends (COE, unpublished data sheets, 1975-1979; 1979b). The variability from year to year at these sites may be partially due to variations in the sample size (from 1 to 26) and within-site patchiness encountered in sampling each year. Concentrations of lead at three of the five sites were relatively low in 1975.

The other data set, which extended over several years at the same sites, was the SBDA study in the southern end of south Bay (Figure 42). From January 1982 through April 1986, the SBDA sampled two sites located in the south Bay basin and two sites in peripheral areas on a quarterly basis. The mean lead concentrations in the surficial sediments were 42 ppm at the beginning of the study period, decreased to 26 ppm in April 1982, then fluctuated between 10 and 30 ppm through April 1984. The largest quarterly increase in lead concentrations occurred between April and July 1984 when the mean concentration went from 16 ppm to 50 ppm. After July 1984, the mean concentration fluctuated between 20 and 50 ppm (Figure 42). However, there were no significant differences between any of the quarterly sampling periods (p=0.05).

When the yearly mean lead concentrations of the NS&T Program data from all the sites were compared for 1984 through 1986, 1984 and 1986 were significantly different (p=0.05). The means for the 3 years were, 17 ppm in 1984, 36 ppm in 1985, and 30 ppm in 1986. However, if the data from one peripheral site sampled in 1985, Islais Creek, were excluded from the calculations, the mean for 1985 would have been 18 ppm. Without the Islais Creek site, the yearly means are 17 ppm in 1984, 18 ppm in 1985, and 36 ppm in 1986; the means for 1985 and 1986 were significantly different (p=0.05)

B. Biota

Lead concentrations have been measured in fish and bivalves by 13 surveys since 1971 (Table 2). Pooling the data from 331 samples of mussels (*Mytilus edulis, M. californianus*) analyzed for lead content since 1971 shows the mean concentration to have been 6.23 ppm (Table 19). Lead concentrations have ranged from less than 0.2 to 519.2 ppm. The median lead concentration has been 2.9 ppm. Highest mean concentrations were found in peripheral areas of the central Bay. Peripheral areas appeared to contain mussels with elevated lead levels over those from basin areas. Median lead levels from the three basins were similar. Mean concentrations in central Bay have been somewhat higher than in San Pablo Bay and south Bay. However, since each basin is unevenly represented in these calculations, the results must be interpreted with caution. Specifically, there are considerable data for central and south Bay, whereas only one value for Suisun Bay was found. The overall median lead level in San Francisco Bay mussels from 1971 through 1986 is elevated over those for mussels collected from Bodega Head and Tomales Bay by factors of about 3 and greater than 14, respectively. The means and ranges in concentrations reported in the various studies of mussels are summarized and compared with the historical Bay-wide grand mean in Figure 43.

(1) Geographic Trends

The analysis of lead in Japanese littleneck clams (*Tapes semidecussata*) or soft-shell clams (*Mya arenaria*) by the U.S. EPA in 1972 (Shimmin and Tunzi, 1974), showed clams from Albany Hills and Bayview Park to be the most contaminated. These clams contained approximately 164.6 and 92.7 ppm, respectively. Clams at the 13 other sites contained 3.6 to 33.6 ppm lead.

The sampling of bay mussels (*Mytilus edulis*) in 1975 (Girvin et al., 1975) showed a wide range in values (Figure 43) and highest levels of lead at Islais Creek (36.9 ppm) and Albany Hills (22 ppm). Mussels at six other south Bay sites had less than 10 ppm lead. Clams sampled during 1975 by the same survey showed highest concentration of lead at Albany Hills (17.7 ppm) compared to less than 5 ppm at sites in south Bay.

In 1980, the sampling of bay mussels (*Mytilus edulis*) from 12 sites in the Bay showed highest concentrations of lead to be detected at peripheral and basin sites at Point Isabel near Berkeley (519.2 and 186.8 ppm) (McCleneghan et al., 1982; Hayes et al., 1985). Lead in mussels from the other sites ranged from 1.0 to 4.0 ppm. The total range in results for the study was remarkably high because of the sample from Point Isabel (Figure 43). Samples analyzed by McCleneghan et al. (1982) showed lead concentrations in mussels to be significantly higher at the Point Isabel sites than at all other sites measured (p=0.05). Mussels at Point Richmond contained significantly lower lead concentrations (1 ppm) than all sites except Coyote Point (3 ppm) (p=0.05). Mussels from San Pablo Bay sites had slightly lower concentrations of lead than those from the central or south Bay sites. Japanese littleneck clams (*Tapes japonica*) sampled in 1980 also showed highest lead levels (15.3 to 1012.5 ppm) at the Point Isabel sites (Figure 44) (Kinney and Smith, 1982; McCleneghan et al., 1982). Clams from San Leandro Creek and from near Virginia Street off Berkeley also contained elevated lead levels (119.2 and 30.0 ppm, respectively). Clams from peripheral areas generally had higher lead levels than those from basin sites. Clams from central Bay sites generally contained higher concentrations of lead than those from sites in the south Bay. Clams analyzed by Kinney and Smith (1982) showed lead concentrations to be significantly higher at the Point Isabel and San Leandro Creek sites (p=0.05). The clams analyzed by McCleneghan et al. (1982) also had significantly higher lead concentrations at the Point Isabel sites than at all other sites (p=0.05), while clams at the Point Richmond site had significantly lower levels than at four other sites. McCleneghan et al. (1982) also sampled *Mya arenaria* from the same sites. Lead levels in *Mya* were significantly higher (8.5 to 9.6 ppm ww) than at the other sites (0.2 to 1.0 ppm ww) (p=0.05).

The NS&T Program (NOAA, 1987a) analyzed lead in the livers of starry flounder (*Platichthys stellatus*) or white croaker (*Genyonemus lineatus*) from four sites in San Francisco Bay and a site in Bodega Bay in 1984 (Figure 45). These analyses showed highest concentrations of lead in liver tissue of starry flounder taken from Southampton Shoal (0.34 ppm). Lowest lead concentrations (0.11 ppm and <0.15 ppm, respectively) were found in liver tissue of starry flounder from San Pablo Bay and Bodega Bay. However, there were no significant differences between sites (p=0.05). The sites and species sampled by the Benthic Surveillance Project of the NS&T Program have not been sampled for lead by other surveys.

In 1985 and 1986, the California State Mussel Watch Program (Hayes and Phillips, 1986; 1987) analyzed lead in coastal mussels (*M. californianus*) transplanted to 8 and 10 sites, respectively, in San Francisco Bay, and in resident mussels from Bodega Head (Figure 46). A wide range in concentrations was observed by California Mussel Watch in 1985 (Figure 43) The highest concentrations of lead were found in mussels transplanted to the Alameda Yacht Harbor (11 to 50 ppm), followed by those in mussels from parts of the Oakland Inner Harbor, where between 4 and 14 ppm were found. Mussels transplanted to basin sites had 2.3 to 3.4 ppm. The residents at Bodega Head had 1.1 ppm lead.

Except in 1985 when high concentrations were detected in transplanted mussels in the Alameda Yacht Harbor, the mussel watch programs of EPA, California Mussel Watch, and the NS&T Program generally reported lead levels near or below the Bay-wide grand mean (Figure 43). Most of the sampling sites of these programs, which resulted in relatively low concentrations, were in basin locations. The exceptions were those in the Alameda Yacht Harbor and Oakland Inner Harbor, both of which were relatively more contaminated than basin sites in 1985 and 1986.

In 1986, the NOAA NS&T Program analyzed lead in resident mussels (*Mytilus edulis* or *Mytilus californianus*) from the San Mateo Bridge, Dumbarton Bridge, Tomales Bay, and Bodega Head (Figure 46). Concentrations of lead in mussels were relatively low at all sites (0.5 ppm, 0.8 ppm, 0.4 ppm, and 1.1 ppm, respectively) (Figure 46). However, only two pairs of sites were not significantly different from one another: San Mateo and Tomales Bay, and Bodega Head and Dumbarton Bridge (p=0.05). The sampling of mussels by the NS&T Program was conducted at sites that had been previously occupied by other surveys. Except for Bodega Head, lead concentrations measured by the NS&T Program were approximately half the mean level previously found by other investigators at the same or nearby sites. At the San Mateo Bridge, the mean lead concentration detected between 1976 and 1986 by Hayes et al. (1985), Hayes and Phillips (1986, 1987), and Risebrough et al. (1978) was 2.09, with a range from 0.9 to 3.1 ppm compared to 0.51 ppm detected by the NS&T Program. At the Dumbarton Bridge, the NS&T Program detected 0.76 ppm in mussels, compared to a mean of 2.23 detected by Risebrough et al. (1978) and Hayes et al. (1985), and Hayes and Phillips (1986, 1987) between 1976 and 1986 (with a range of 0.8 to 3.1 ppm). At Tomales Bay, Hayes et al. (1985), Hayes and Phillips (1986, 1987), Wyland (1975), and Anderlini et al. (1975a, b) found a mean level of lead of 0.41 ppm (with a range of <.2 to 3.1) between 1973 and 1982, while the NS&T Program detected 0.42 ppm. At Bodega Head, Hayes et al. (1985, 1986a, b) and Farrington et al. (1982) found a mean level of 0.92 ppm in mussels, and the NS&T Program detected 1.1 ppm.

(2) Temporal Trends

Resident mussels (*Mytilus spp.*) have been resampled at four sites since 1975 for lead analyses. Sampling at Foster City or nearby on the San Mateo Bridge in 1975, 1982, and 1986 has indicated similar values (from <3.3 to 1.3 to 0.5 ppm) in lead concentrations (Girvin et al., 1975; Hayes et al., 1985; Boehm et al., 1987). Sampling at Redwood Creek (and at two sites nearby) in 1975, 1980, and 1982 indicated a possible decline in lead levels (from 9.8 to 3.2 to 4.9 ppm) (Girvin et al., 1975; Hayes et al., 1985). Sampling at the Dumbarton Bridge in 1980, 1982, and 1986 suggested a slight decline in lead concentrations (from 1.6 to 0.8 to 0.76 ppm) (Hayes et al., 1985; Boehm et al., 1987). Resampling of mussels from Bodega Head showed no significant change in lead levels (range=0.8 to 1.5 ppm) since 1977 (p=0.05) (Hayes et al., 1985; Hayes and Phillips, 1986, 1987).

Clams (*Tapes spp.*) have been resampled in two areas of San Francisco Bay since 1972. Sampling at Foster City in 1972, 1975, and 1980 indicated that lead concentrations have remained near 2 to 3 ppm since 1972 (Shimmin and Tunzi, 1974; Girvin et al., 1975; McCleneghan et al., 1982). Samples taken in the same studies in 1972, 1975, and 1980 from Albany Hill or nearby at Point Isabel indicate a possible decline in lead levels from approximately 164.6 ppm to 17.7 ppm to 15.3 ppm.

Transplanted mussels (*Mytilus californianus*) have been resampled at eight sites in San Francisco Bay since 1979 (Figure 47). No consistent trends in lead levels were apparent from these analyses. Most of the samples had 1 to 4 ppm lead over 4- to 7-year sampling periods.

C. Summary

Like many other trace metal concentrations, lead concentrations in the sediments of San Francisco Bay and its environs display a small scale-patchiness and a large-scale homogeneity. This pattern is illustrated in Figure 38, where lead concentrations for individual samples ranged from 1 to 10,000 ppm (a difference of 10,000 times), but mean concentrations for each study ranged from 12 to 241 ppm (a difference of 20 times). If the single highest and lowest samples and means were excluded, then the sample range would become 1 to 3,000 ppm (a difference of 3,000 times), while the mean range would become 17 to 107 ppm (a difference of only 6.3 times). The mean concentrations for the studies exceeded 100 ppm in only two instances; a USGS study in 1973, which included the 10,000 ppm sample, and a CH^2M-Hill study in 1979, which included data from areas affected by sewer overflows.

The means, standard deviations, medians, and ranges of lead concentrations in the sediments of the four basins and selected peripheral areas based on data from all the studies compiled for this report are listed in Table 20. The table also includes the number of samples taken at each area and the years in which sampling took place. While the table orders the areas from highest to lowest mean, any comparisons of areas must be done with extreme caution because of differences in sampling and analytical methodologies, time of sampling, and number of samples taken at each area. Possibly the most significant statistics in Table 20 are the ranges that show a high degree of overlap for all the areas sampled, both basins and peripheral areas. The 11 highest means, as well as the 3 lowest means, are for peripheral areas, but the standard deviations are very high and the ranges in values overlap those from the four basins. Peripheral areas that have had relatively high lead concentrations include China Basin, Oakland Inner Harbor, Islais Creek, San Leandro Bay, and Redwood City Harbor. Concentrations in China Basin (maximum = 3,000 ppm) have exceeded those in Tomales Bay (20 ppm) by a factor of 150. The grand mean for the Bay (56 ppm, Table 16) exceeds the mean concentrations for two reference sites, Bodega Bay (1 ppm) and Tomales Bay (20 ppm) by factors of 56 and 2.8, respectively.

The available data indicate that lead concentrations in the sediments of San Francisco Bay display a small-scale patchiness and a large-scale homogeneity, with the basins having a slightly lower mean lead concentration than the peripheral areas (Table 16). The existence of this pattern is supported by the USGS study in 1970 where the basin mean was 30 ppm and the peripheral mean was 279 ppm. Additional support comes from CH^2M-Hill's 1979 study that showed a pattern of decreasing lead concentrations from the head to the mouth of both China Basin and Islais Creek.

Central Bay biota frequently have been most highly contaminated with lead as compared to those from San Pablo Bay and south Bay. Mussels from the Point Isabel peripheral area near Berkeley have had especially high concentrations (Table 19). Some samples of clams have also had very high lead concentrations there. Levels have also been high in the Alameda Yacht Harbor, Oakland Inner Harbor, and San Leandro Creek areas. The grand median concentration in mussels from the Bay is above those of Bodega Head and Tomales Bay by factors of about 3 to over 14; the grand mean concentration is elevated by factors of about 6.7 to 15.

Most of the studies performed with biota in the Bay have shown narrow ranges in lead concentrations (Figure 42). The exceptions have been those where mussels from either Point Isabel, Alameda Yacht Harbor, Oakland Inner Harbor, or San Leandro Bay were sampled. The mussel watch sampling sites of EPA, California Mussel Watch, and the NS&T Program in the basins have indicated relatively low and *monotonous* lead concentrations. The highest concentration found thus far in the Bay (519.2 ppm) exceeds the Bay-wide grand mean by a factor of 83 times, whereas the basin means and medians either do not exceed the grand Bay-wide means and medians or do so by factors of less than 2 times.

The available data indicated yearly fluctuations in lead concentrations in sediments, but no long-term trend was apparent. There was a possible decrease in lead contamination in the mid 1970s (Figure 41) that might be indicative of the drought experienced by California at that time.

The small record of lead concentrations in biota precludes determining Bay-wide, long-term temporal trends. From the available data from the past 10 years or thereabouts, no major changes in concentrations have occurred, with the possible exception of an apparent decline at the Point Isabel area. However, the data record there is poor based upon data from only three sampling periods, two sampling sites, and two laboratories. The state and federal mussel watch data from basin sites indicate relatively uniform concentrations since the mid 1970s.

Historical mean concentrations of lead in sediments sampled from 1972 through 1986 in San Francisco Bay are compared in Figure 48 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper-case print. The NS&T Program sites are in lower-case print. Those from the 1984 Benthic Surveillance Project are designated by "BS" after the site name; those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold, lower-case print. The historical overall mean for the Bay (56 ppm) was ranked very high compared to the NS&T Program sites, exceeding all of them in lead concentration. The means for the peripheral sites and for China Basin also exceeded the means for all the other sites. The historical means for the basins were not particularly high. Among the NS&T Program sites sampled in 1984 and 1986, two in the Bay were ranked in the top ten: off Yerba Buena Island and off the Alameda NAS. Three sites were ranked in the lowest eleven. The reference sites, Tomales Bay and Bodega Bay, ranked 23rd and last, respectively.

The historical mean concentrations of lead in mussels collected in San Francisco Bay from 1972 through 1986 are compared in Figure 49 with means from three samples of mussels each from NS&T Program Pacific Coast sites sampled in 1986. The historical areas are designated in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located within the Bay are listed in bold print. The means from historical analyses of samples from the Bay were relatively high compared to the 1986 values for Pacific Coast sites. The grand mean for the Bay and the overall mean for central Bay were exceeded only by the concentrations at three 1986 NS&T Program sites. The exceptionally high concentrations of lead in the Point Isabel area are illustrated with these data. The 1986 mussels from the two NS&T Program sites in the Bay were not particularly contaminated with lead, ranking 34th and 43rd. The two reference sites, Tomales Bay and Bodega Head, ranked last and 25th, respectively.

Table 16. Bay-wide means, standard deviations, medians, and ranges of lead concentrations in surficial sediments of San Francisco Bay based on data collected by many investigators from 1970 through 1987 from the four basins and peripheral harbors and waterways (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	56	300	38	1 - 10000	1314
BASINS	32	27	30	1 - 421	461
PERIPHERY	69	371	43	2 - 10000	853

Table 17. Means, standard deviations, medians, and ranges of lead concentrations in surficial sediments of San Francisco Bay for 1970, based on USGS data (Peterson et al., 1972) (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
BASINS					
CARQUINEZ STR/SUISUN BAY	22	22	10	5 - 100	35
SAN PABLO BAY	35	17	30	10 - 70	23
CENTRAL BAY	31	24	30	5 - 70	41
SOUTH BAY	32	19	30	5 - 100	43
BASIN TOTAL	30	22	30	5 - 100	142
PERIPHERY					
CARQUINEZ STR/SUISUN BAY	75	247	10	5 - 1000	16
SAN PABLO BAY	1467	3763	50	10 - 10000	7
SOUTH BAY	155	462	70	5 - 3000	41
PERIPHERY TOTAL	279	1295	50	5 - 10000	64

Table 18. Yearly ranking of areas, from highest to lowest lead levels, sampled by the COE from 1971 through 1979, based on the ANOVA and Scheffé's F-test of the log transformed data (bars connect those areas which are not significantly different at p=0.05) .

1971*	1972*	1973*
OAKLAND OUTER HBR OAKLAND INNER HBR RICHMOND HARBOR PETALUMA RIVER PINOLE SHOALS SAUSALITO CHANNEL ISLAIS CREEK SAN BRUNO CHANNEL	REDWOOD CITY HBR SAN LEANDRO MARINA ALAMEDA NAS MARE ISLAND STRAIT OAKLAND OUTER HBR PT MOLATE RICHMOND HARBOR PETALUMA PT DAVIS	ALAMEDA NAS OAKLAND INNER HBR PETALUMA PETALUMA RIVER PINOLE SHOALS CARQUINEZ STRAIT N SAN FRANCISCO BAY
1974	**1975**	**1976**
OAKLAND INNER HBR MARE ISLAND STRAIT OAKLAND OUTER HBR ISLAIS CREEK RICHMOND HARBOR RICHMOND HBR CHNL ALAMEDA NAS PT MOLATE	RICHMOND HBR CHNL MARE ISLAND STRAIT PINOLE SHOALS OAKLAND OUTER HBR OAKLAND INNER HBR	BERKELEY BREAKWATER OAKLAND OUTER HBR OAKLAND INNER HBR MARE ISLAND STRAIT ALAMEDA NAS RICHMOND HBR CHNL PETALUMA SUISUN BAY
1977	**1978**	**1979**
OAKLAND OUTER HBR MARE ISLAND STRAIT RICHMOND HBR CHNL OAKLAND INNER HBR	OAKLAND INNER HBR OAKLAND OUTER HBR MARE ISLAND STRAIT RICHMOND HBR CHNL ALAMEDA NAS	OAKLAND OUTER HBR OAKLAND INNER HBR RICHMOND HBR CHNL MARE ISLAND STRAIT

* Excludes areas with less than three samples.

Table 19. Means, medians, and ranges in concentration of lead in mussels (Mytilus edulis or Mytilus californianus) collected by many investigators in 1971-1986, in basins and peripheral areas of San Francisco Bay (ppm dw)

AREA/SITE	MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY	2.90		-	-	1
SAN PABLO BAY					
BASIN	2.45	1.92	2.15	1.1-10.4	32
PERIPHERAL-MARE ISL. STRAIT	2.89	2.85	1.85	<0.1-11.8	24
CENTRAL BAY					
BASIN	7.57	35.5	3.70	1.0-366.4	105
PERIPHERAL-RICHMOND HARBOR	4.12	1.36	4.20	2.4-5.7	4
POINT ISABEL	266	358	-	12.5-519.2	2
BERKELEY					
BERKELEY MARINA	0.24	0.49	<0.2	<0.2-1.8	12
ALL PERIPHERAL	30.62	122	<0.2	<0.2-519.2	18
SOUTH BAY					
BASIN	3.04	2.14	2.80	<0.2-8.5	98
PERIPHERAL-ISLAIS CREEK	36.90	-	-	-	1
NEWARK SLOUGH	2.50	-	-	-	1
ALAMEDA YACHT HARBOR	30.64	27.8	-	10.98-50.3	2
OAKLAND INNER HARBOR	7.69	5.24	7.03	2.8-13.9	4
OAKLAND OUTER HARBOR	1.10	-	-	-	1
BAYSHORE LAGOON	3.73	2.91	-	1.7-5.8	2
PALO ALTO YACHT HARBOR	2.47	1.12	2.90	1.2-3.3	3
REDWOOD CREEK	3.12	3.47	1.80	<0.2-12.7	32
BELMONT SLOUGH	2.30	-	-	-	1
ALVISO SLOUGH	4.30	-	-	-	1
ALL PERIPHERAL	5.31	9.04	2.80	<0.2-50.3	47
ALL S.F. BAY	6.23	34.9	2.90	<0.2-519.2	331
TOMALES BAY	0.41	0.56	<0.2	0.4-3.1	36
BODEGA HEAD	0.93	0.38	0.90	0.3-2.2	53

Table 20. Means, standard deviations, medians, and ranges of lead concentrations in the surficial sediments of San Francisco Bay for the four basins and selected peripheral areas based on data collected by many investigators from 1970 through 1987, ordered from highest to lowest by mean (ppm dw).

AREA	YEARS SAMPLED	MEAN	S D	MEDIAN	RANGE	NO. of SAMPLES
CHINA BASIN	79	852	1187	339	4 - 2580	4
SAN LEANDRO BAY	80-81	126	75	120	20 - 280	15
ISLAIS CREEK	70, 71, 74, 79, 85	102	194	44	5 - 882	20
OAKLAND INNER HBR	71, 73-79	97	338	58	2 - 3000	77
REDWOOD CITY HBR	71-74	87	74	68	11 - 286	18
BERKELEY MARINA	80-81	82	27	75	40 - 140	15
OAKLAND OUTER HBR	71-81	56	38	49	6 - 224	81
ALAMEDA NAS	71-74, 76, 78	47	26	51	8 - 150	62
MARE ISLAND STR	70-79	47	13	46	22 - 124	196
HUNTERS POINT NS	72-74, 86, 87	45	16	48	11 - 70	20
RICHMOND HARBOR	71-79	39	21	37	10 - 153	112
CENTRAL BAY	70,71,73,74,76,80,81,84-86	34	27	30	3 - 170	134
GUADALOPE SLOUGH	82-86	34	12	34	10 - 52	20
SAN PABLO BAY	70-73, 75-76, 84-86	32	40	27	5 - 421	112
COYOTE CREEK	82-86	32	13	32	14 - 66	20
PT MOLATE	71, 72, 74	30	13	38	8 - 46	17
SOUTH BAY	70,71,73,74,79,80,82-86	30	18	30	1 - 100	124
CARQUINEZ STR./SUISUN BAY	70, 73, 74, 83	29	18	30	1 - 100	89
CASTRO COVE	81	26	17	24	2 - 75	43
GALLINAS CREEK	81	21	17	13	6 - 77	27
CORTE MADERA CREEK	81	13	9	10	2 - 36	24
BODEGA BAY	84-85	1	1	0.5	0.1 - 3	6
TOMALES BAY	86	20	2	20	19 - 22	3

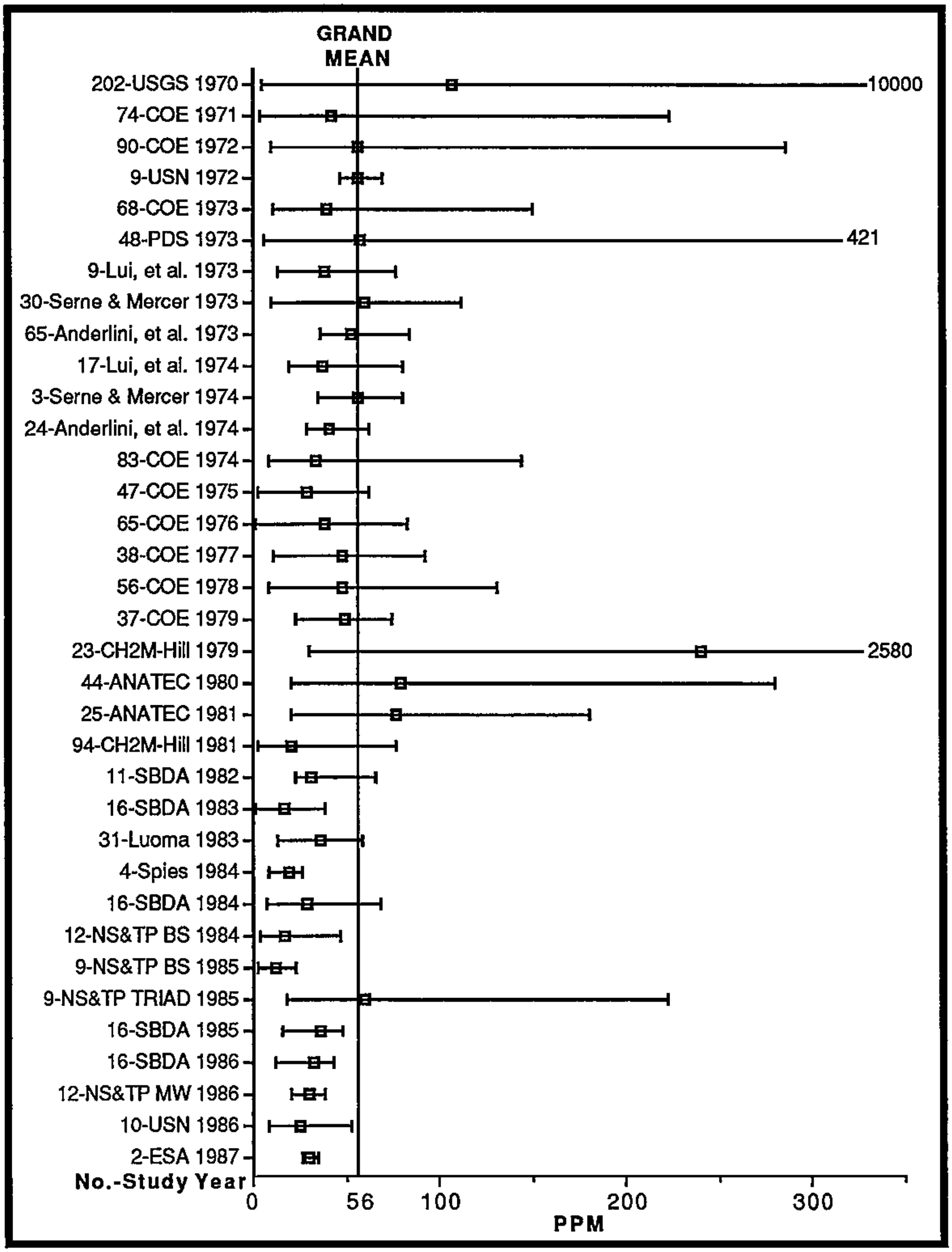


Figure 38. Mean concentration of lead in the surficial sediments of San Francisco Bay by study and year compared to the grand mean for the Bay (ppm dw) (No.=number of samples, bars represent the range).

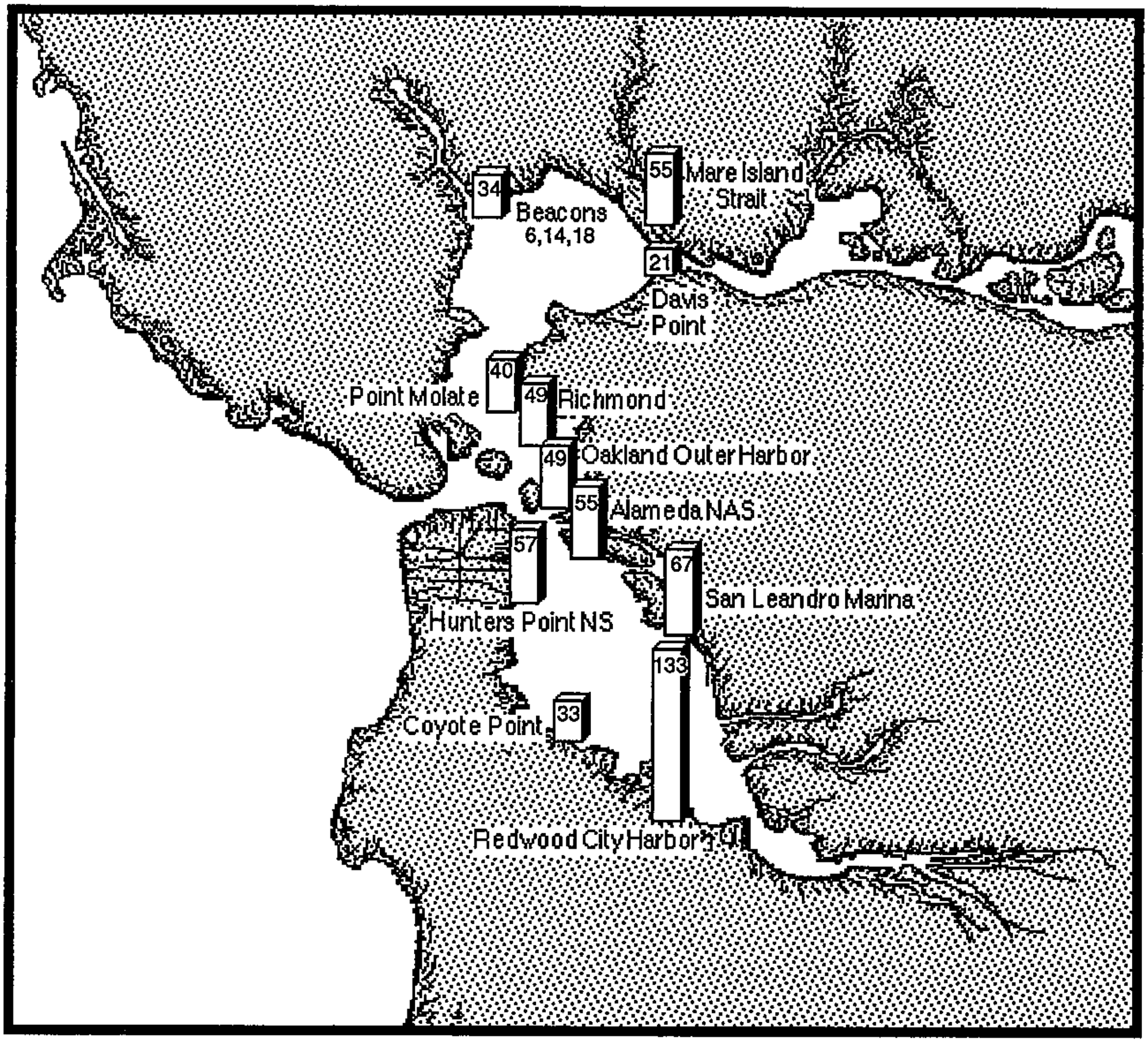


Figure 39. Mean lead concentrations in San Francisco Bay sediments, in ppm dw, based on 1972 dredging studies (COE, 1979a; U.S. Navy, 1972).

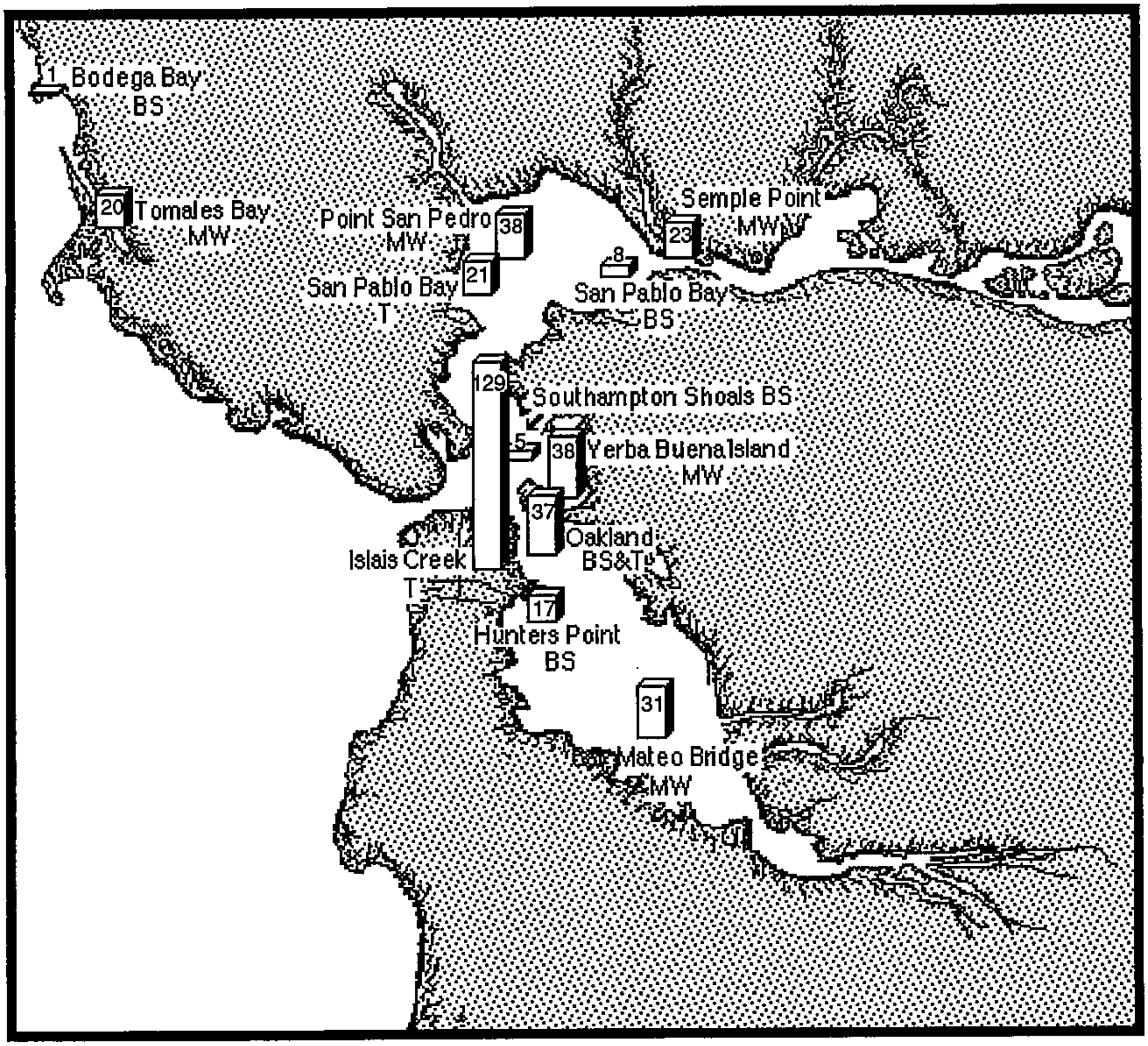


Figure 40. Mean lead concentrations in the surficial sediments of San Francisco Bay for 1984-86, in ppm dw, based on NOAA NS&T Program data (BS=Benthic Surveillance, MW=Mussel Watch and T=Sediment Quality Triad study) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986) .

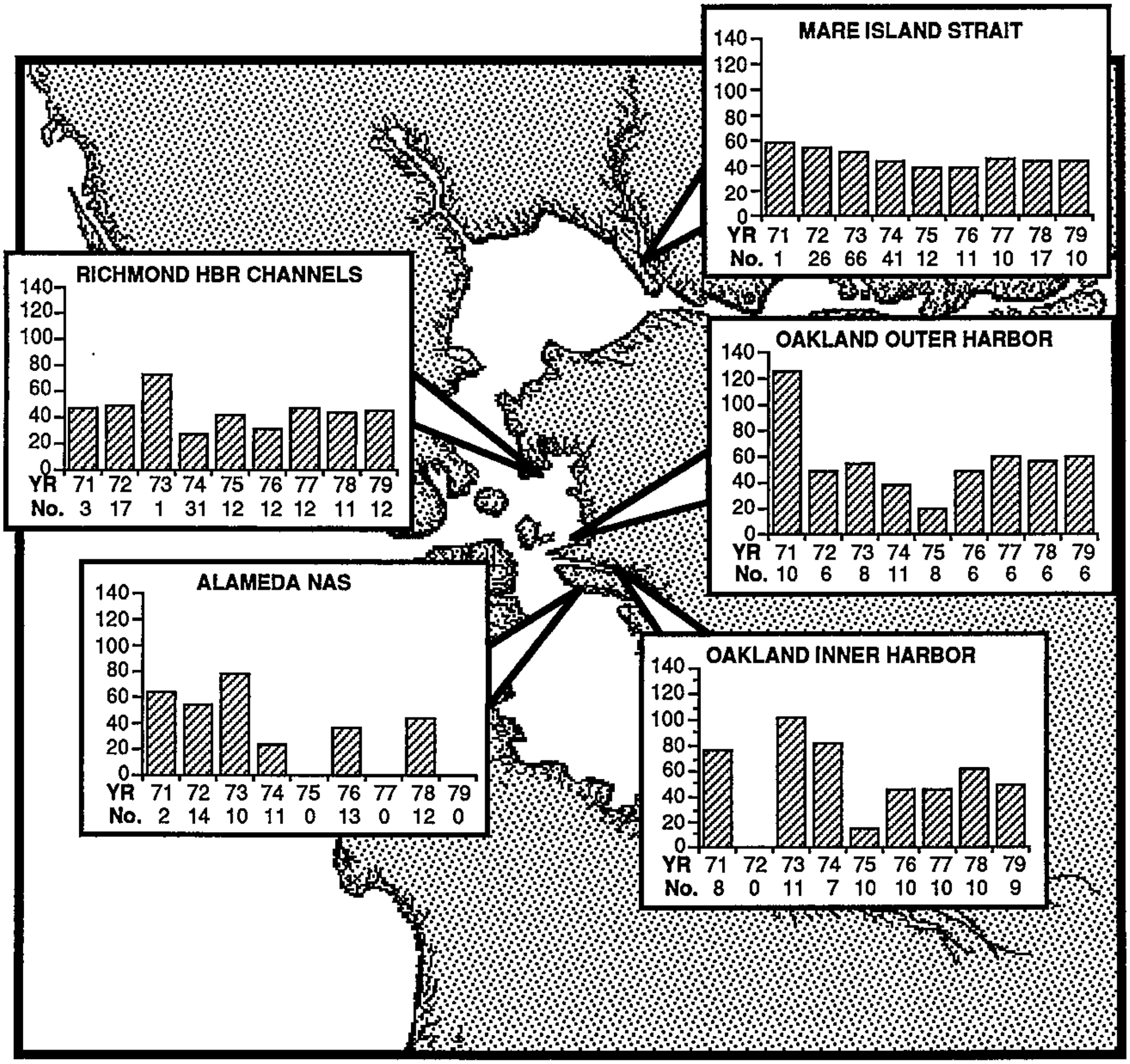


Figure 41. Mean lead concentrations, in ppm dw, at five sites from 1971 to 1979, based on dredging studies (COE, unpublished data sheets1975-79, 1979b).

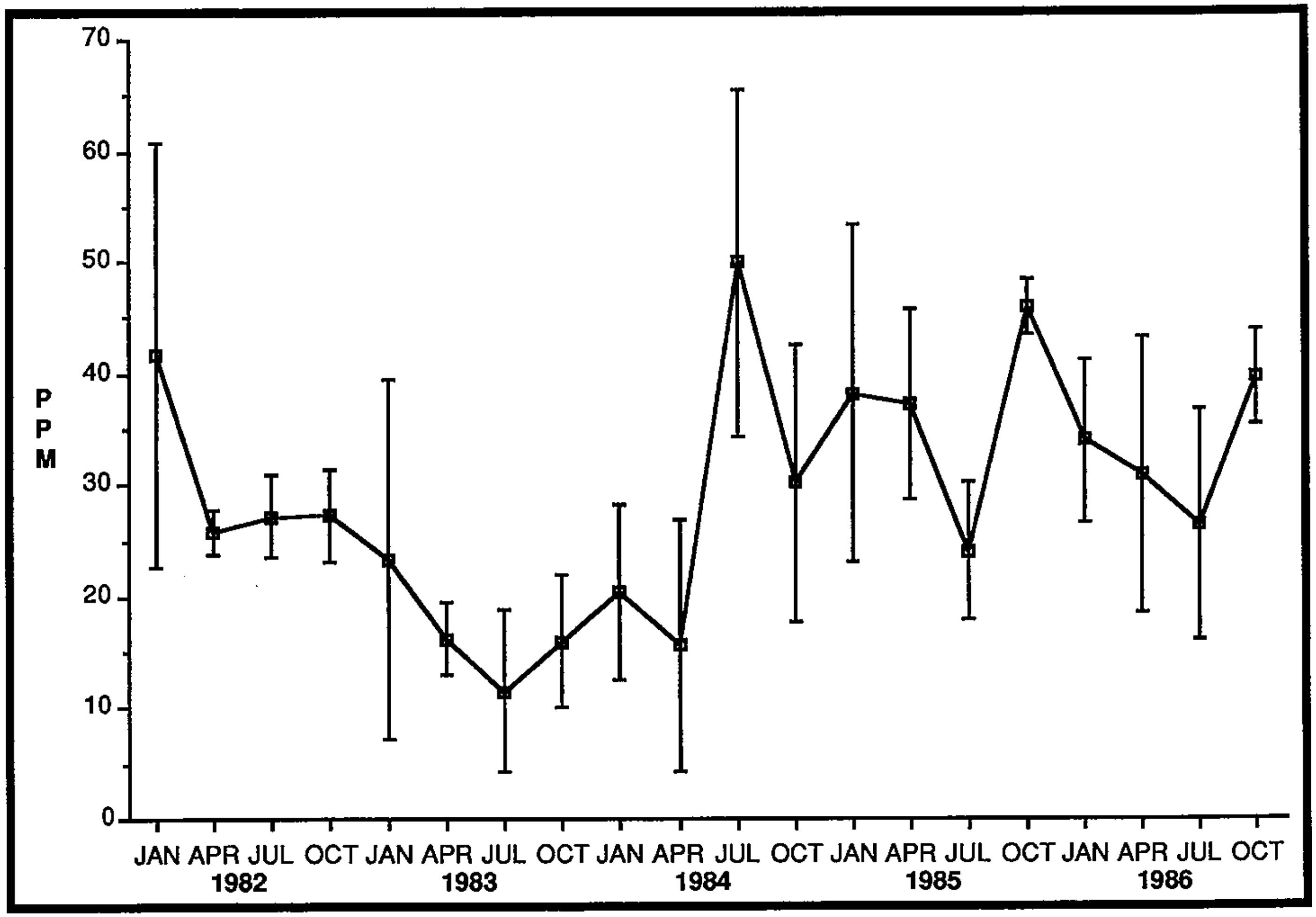


Figure 42. Monthly mean lead concentration in the surficial sediments at the four sites in the southern end of south Bay sampled by the SBDA from 1982 to 1986 (bars represent one standard deviation) (Stevenson et al., 1987).

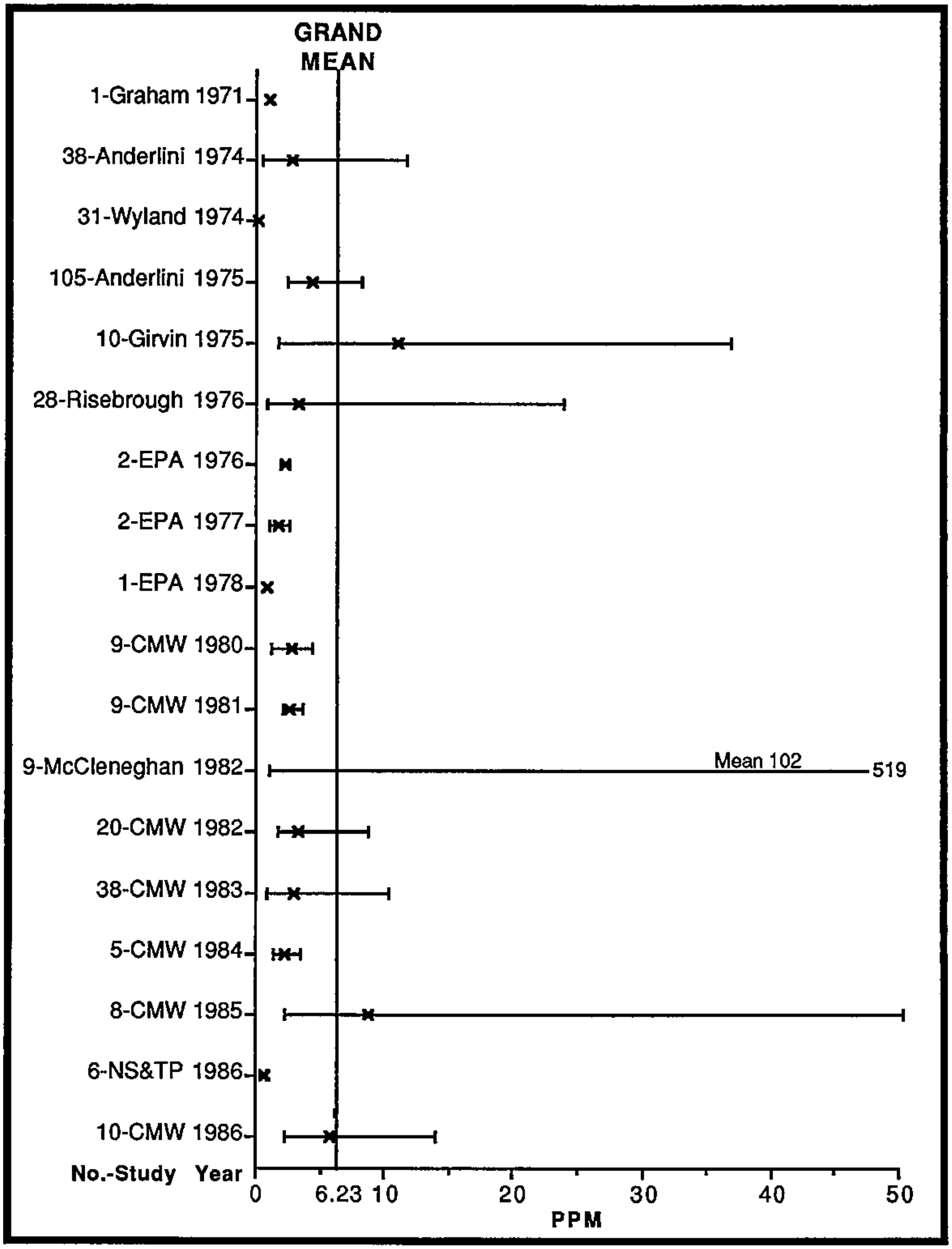


Figure 43. Mean concentration of lead in mussels (Mytilus edulis, M. californianus) by study and year in ppm dw (No.=number of samples, bars represent the range).

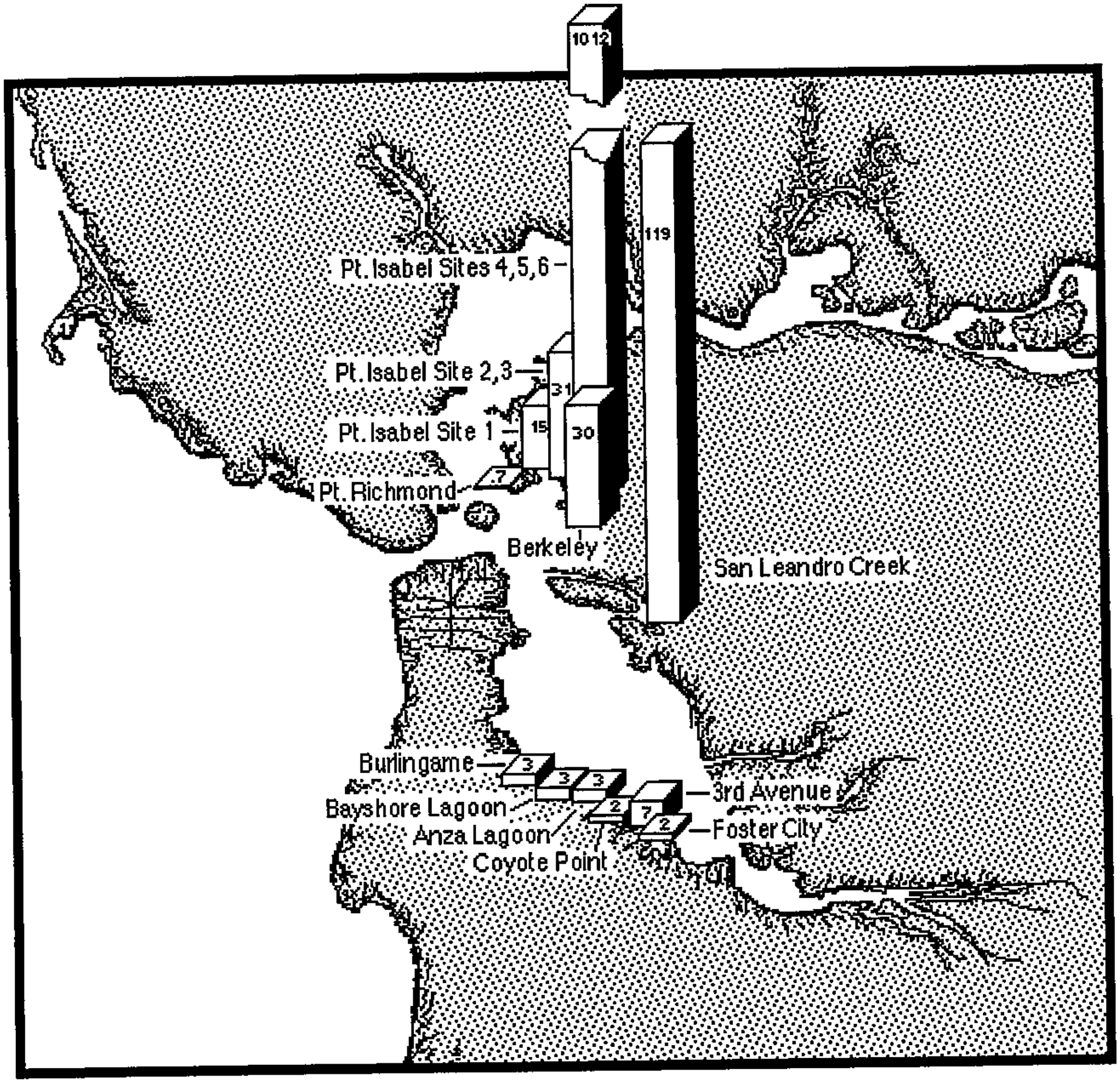


Figure 44. Lead concentrations in Japanese littleneck clams (Tapes japonica) in 1980 (ppm dw) (McCleneghan et al., 1982; Kinney and Smith, 1982).

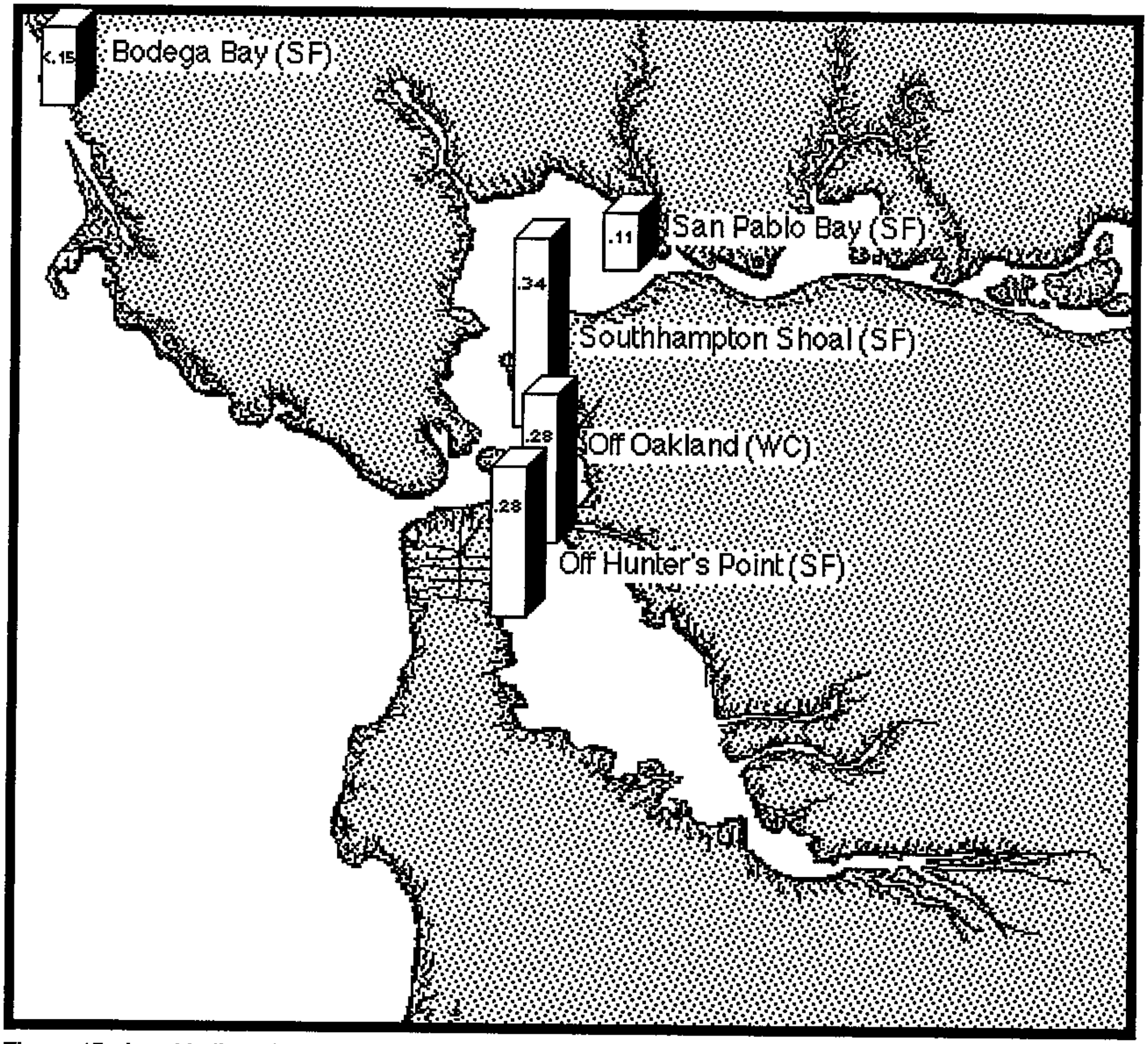


Figure 45. Lead in liver tissue of starry flounder (SF), Platichthys stellatus, and white croaker (WC), Genyonemus lineatus, sampled in 1984 (NOAA, 1987a).

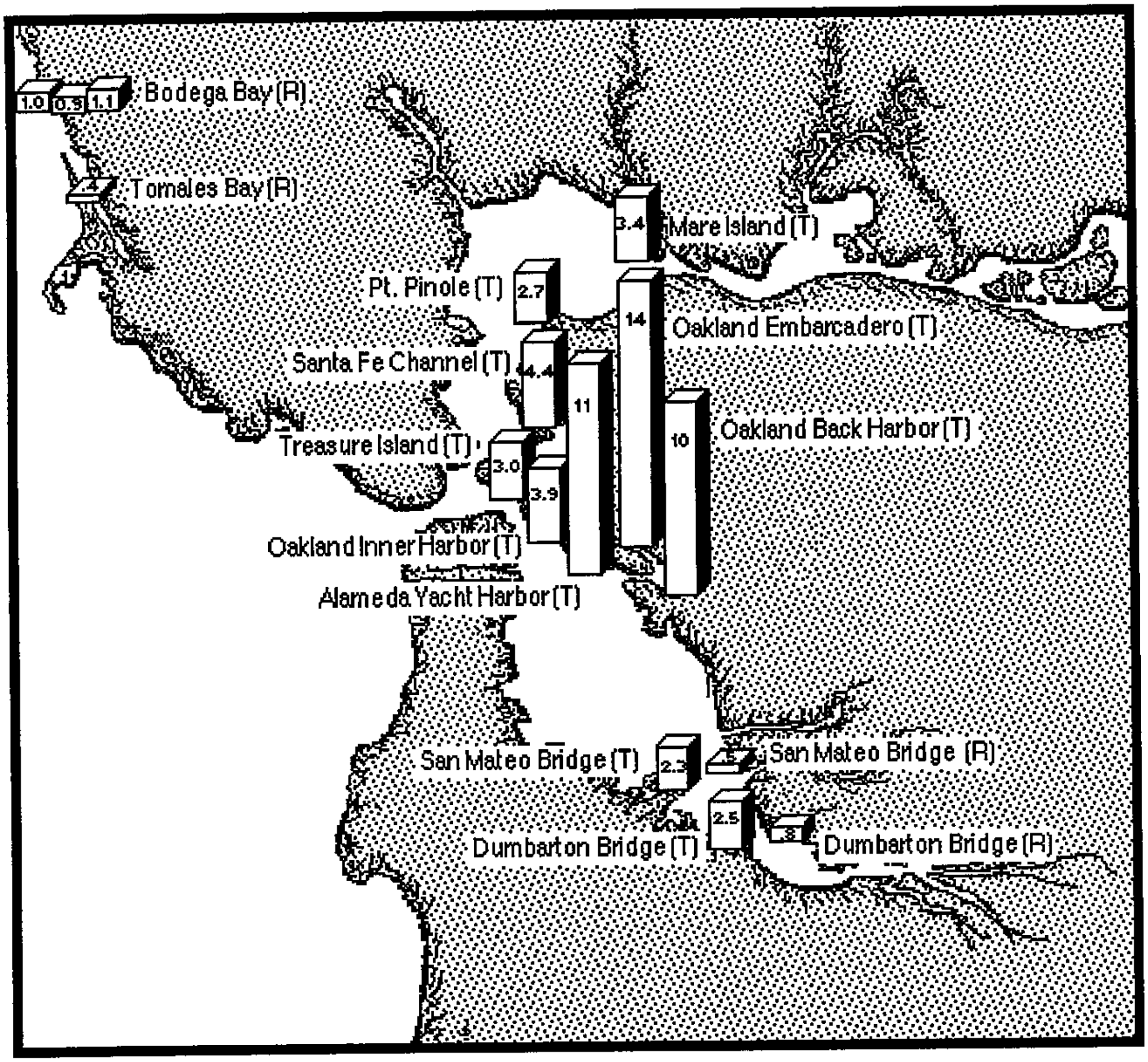


Figure 46. Lead in transplanted (T) coastal mussels (Mytilus californianus) and resident (R) bay mussels (M. edulis) sampled in 1985-86 by CMW and NS&T Program (Hayes and Phillips, 1987; Boehm et al., 1987).

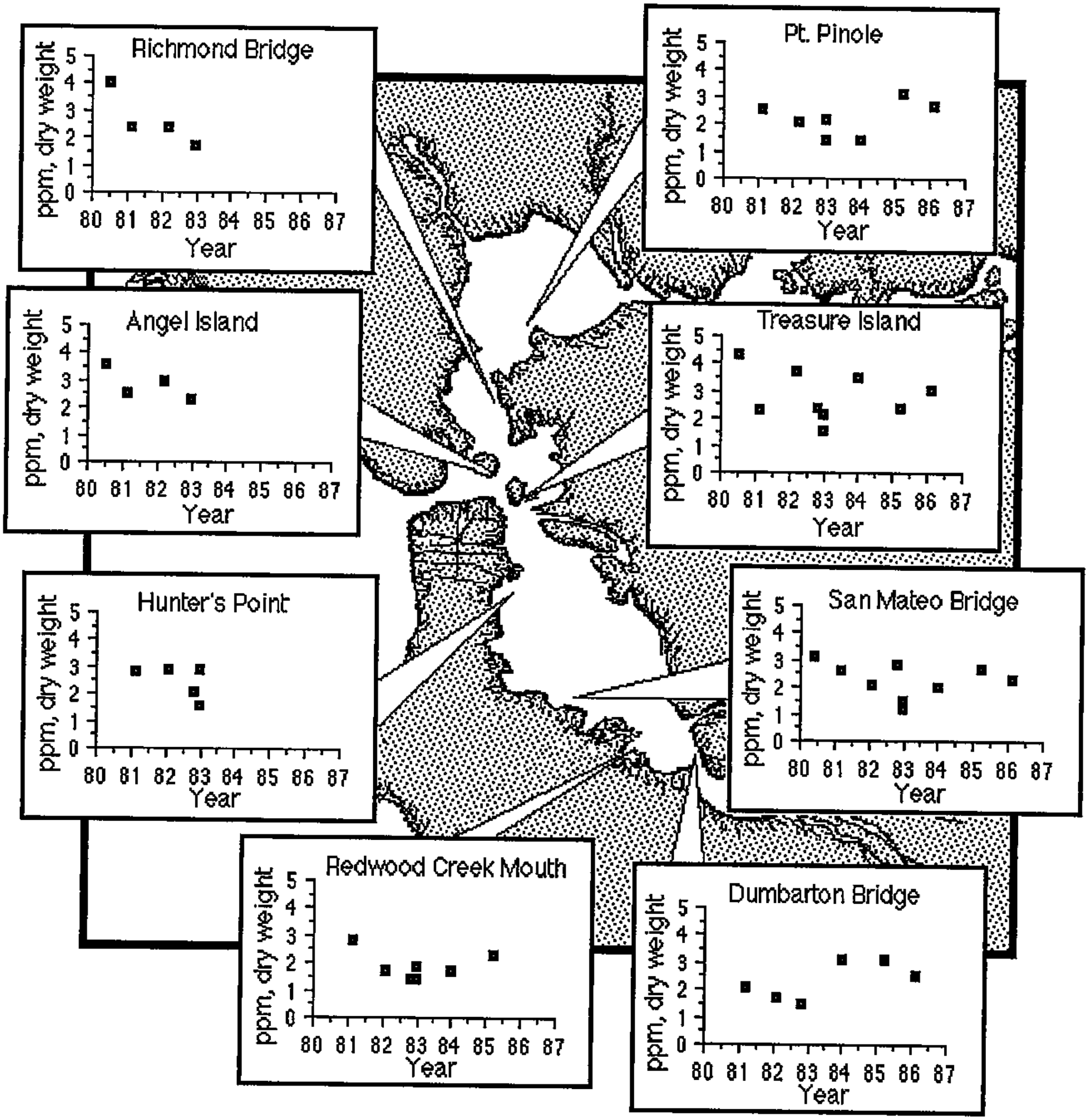


Figure 47. Temporal trends in lead concentrations in transplanted mussels (M. californianus) 1980-1986 (Hayes et al., 1985 and Hayes and Phillips, 1986, 1987).

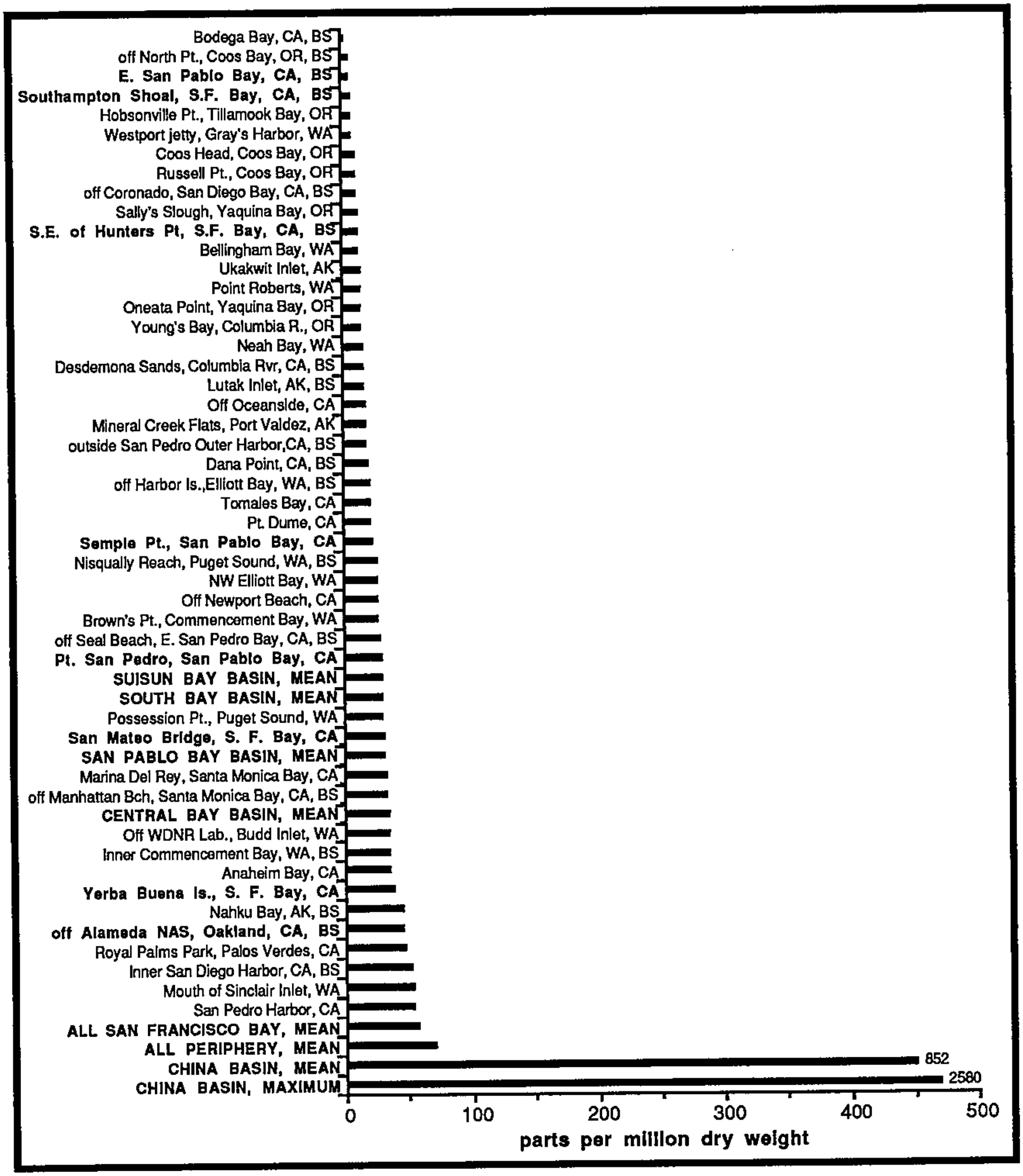


Figure 48. Comparison of lead concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Tables16, 20), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name) .

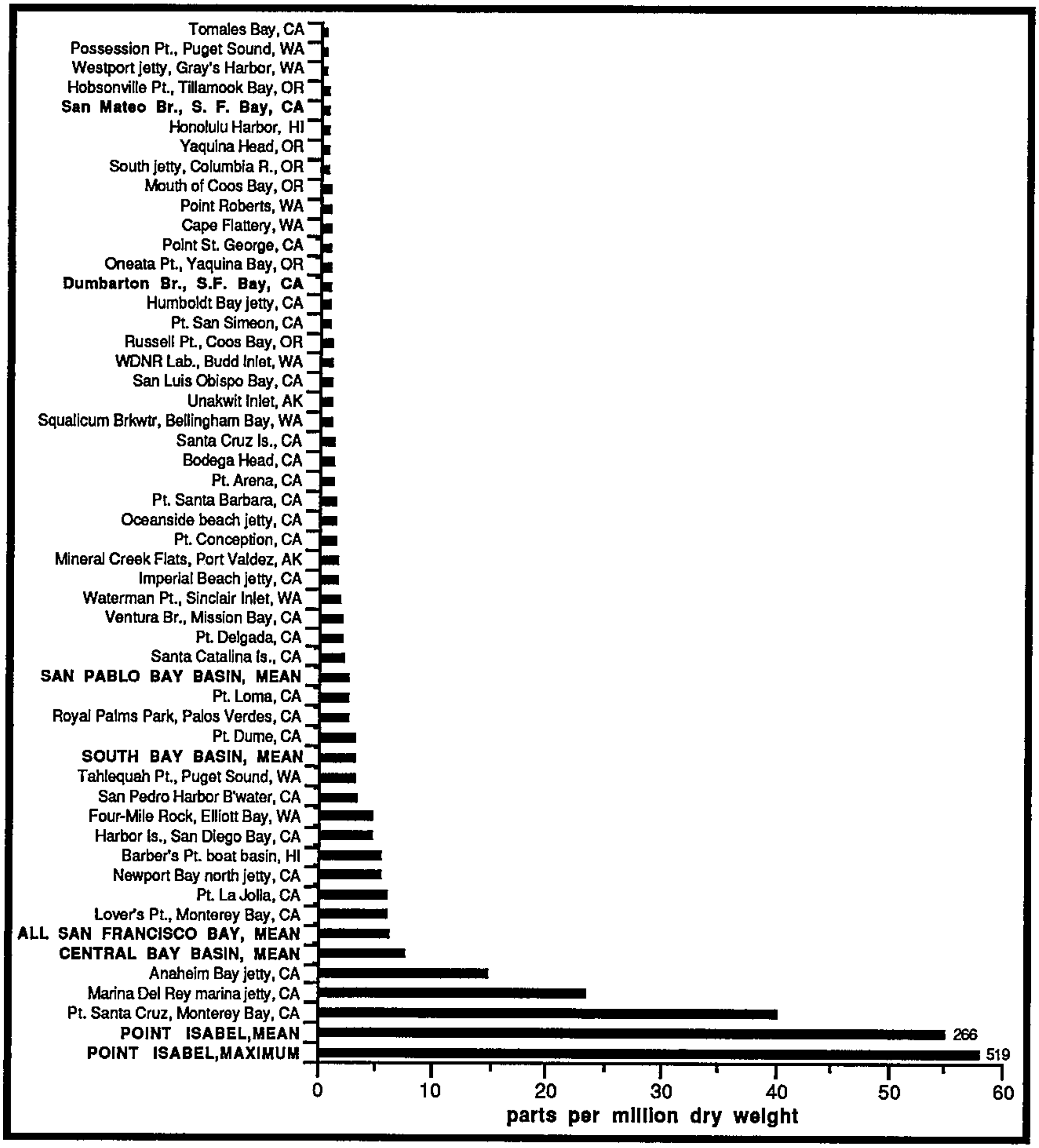


Figure 49. Mean lead concentrations in resident mussels (Mytilus edulis, M. californianus) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1972-1986) data for San Francisco Bay (from Table 19). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

7

GEOGRAPHIC AND TEMPORAL TRENDS IN CHROMIUM CONTAMINATION

A. Sediments

Data on the concentration of chromium in the surface sediments of San Francisco Bay and its environs have been compiled by several investigators sporadically during the period 1971 through 1987 (Table 1). Based on 396 samples collected throughout the system, the grand mean concentration of chromium in San Francisco Bay sediments for the last 17 years was 89 ppm with a standard deviation of 96 ppm and a range of from less than 8 to 769 ppm (Table 21). The vast majority of the chromium values (76 percent) were between 10 and 100 ppm inclusive; less than 1 percent were less than 10 ppm, while 23 percent were greater than 100 ppm. The median value was 63 ppm.

(1) Geographic Trends

In 1971 and 1972, dredging studies were conducted in several harbors and channels of San Francisco Bay under the auspices of the COE (COE, 1979b). The 1971 studies analyzed sediment samples from seven areas, with the number of samples ranging from 1 to 17 per area (only one area had more than four samples). The 1972 studies sampled four areas, with the number of samples ranging from 6 to 26 per area. In addition, the sampling depth varied from sample to sample, ranging from the upper 9 inches to the upper 2.5 feet. The areas sampled during this time were: Mare Island Strait, Richmond Harbor, Oakland Outer Harbor, Alameda Naval Air Station, off Point Molate, Sausalito Channel, San Bruno Channel, Islais Creek , and Redwood City Harbor. The yearly means were 25 ppm in 1971 and 124 ppm in 1972 (Figure 50). The difference between the two yearly means was largely due to several samples collected in 1972 from Richmond Harbor (which was not sampled in 1971) and from Mare Island Strait (which had only one sample in 1971) having chromium concentrations ranging from 100 to 387 ppm. The combined mean for the 2 years of sampling was 84 ppm with a range of from 8 to 387 ppm. The four areas sampled in 1972 (Mare Island Strait, Richmond Harbor, Oakland Outer Harbor, and Redwood City Harbor) were found to be significantly different (more contaminated) than the three areas sampled only in 1971 and for which there were more than two samples analyzed (Sausalito Channel, San Bruno Channel, and Islais Creek) ($p=0.05$). Figure 51 displays the results of the dredging studies for 1971 and 1972.

As part of the COE's intensive dredging study, Serne and Mercer (1975) analyzed a total of 30 sediment samples from eight areas for chromium concentrations in August, 1973. The means ranged from a low of 192 ppm in Richmond Harbor Channel to a high of 383 ppm at Southampton Shoal. Statistical analysis of the data indicated no significant differences between areas sampled ($p=0.05$).

CH2M-Hill prepared a report in 1979 for the City and County of San Francisco on the effects of untreated sewage overflows on the eastern portion of south San Francisco Bay (CH2M-Hill, 1979). Sediments from the upper 10 to 13 cm at 23 sites between China Basin and Brisbane Lagoon were analyzed for chromium. Multiple samples (two to five) were collected at each site. The overall mean concentration of chromium at the 23 sites was 156 ppm with the means of the individual sites ranging from 47 to 534 ppm (Figure 50). The highest chromium concentration (534 ppm) was found at the head of the Islais Creek Waterway, and decreased at each site from the head to the mouth; the chromium concentration at the site at the mouth of the Waterway was 118 ppm. Unlike the other metals, the pattern of decreasing concentrations from the head to the mouth of a channel was not observed in China Basin. The lowest chromium concentration (47 ppm) was found at the site in Candlestick Cove. Of the 23 sites sampled, 18 had means between 100 and 200 ppm.

ANATEC and Kinnetic Laboratories conducted a monitoring program for the East Bay Municipal Utility District in 1980 and 1981 (Kinney & Smith, 1982). They analyzed 69 samples of the upper 10 cm of sediment from six areas (Oakland Outer Harbor, San Leandro Bay, off the Stege Plant, Berkeley Flats, Berkeley Marina, and west of Alameda Island). The overall mean chromium concentration for the study was 53 ppm with a standard deviation of 20 ppm and a range of 18 to 120 ppm (Figure 50). The means for the individual sampling areas ranged from a low of 49 ppm off the Stege Plant to a high of 63 ppm in San Leandro Bay. There were no significant differences between any of the sampling areas (p=0.05).

In 1981 CH^2M-Hill (1981) conducted a study for the Castro Cove refinery of Chevron USA. They collected a total of 94 sediment samples from 29 sites in three areas: Castro Creek and marsh, Gallinas Creek, and Corte Madera Creek. Sampling was conducted on a quarterly basis from March through December 1983. The upper 15 cm of sediment were analyzed for chromium contamination. The overall mean chromium concentration for the study was 66 ppm with a standard deviation of 29 ppm and a range of from 16 to 170 ppm (Figure 50). The mean chromium concentrations for the three areas were: 61 ppm for Castro Creek, 79 ppm for Gallinas Creek, and 60 ppm for Corte Madera Creek. The highest concentration (170 ppm) was found in Gallinas Creek. Analysis indicated that only Gallinas and Castro Creeks were significantly different from each other (p=0.05).

Spies et al. (1985b) collected and analyzed sediment samples from four sites (western San Pablo Bay, west of Berkeley, west of Oakland, and off the western end of Alameda Island) in San Francisco Bay in 1984. The overall mean for the four sites was 28 ppm, while the site means ranged from 14 ppm at the Alameda site (two samples) to 34 ppm at the Berkeley site (three samples) (Figure 50).

The SBDA conducted a 5-year monitoring program from 1982 through 1986 at four sites in the southern end of south Bay (Stevenson et al., 1987). They sampled the upper 5 cm of the sediments. Two of the sites were located in the basin of south Bay, one slightly north of Dumbarton Bridge and the other about midway between the bridge and the mouth of Coyote Creek. The other two sites were located in peripheral areas of the Bay, one in Coyote Creek and the other in Guadalupe Slough. The overall mean concentration of chromium in the sediments at the four study sites over the 5-year period was 38 ppm. The overall means for the individual sites for the same period ranged from 37 to 41 ppm. There were no significant differences between any of the sites during the study period (p=0.05).

In 1984, the Benthic Surveillance Project (BS) of NOAA's NS&T Program began analyzing samples of the upper 3 cm of sediment for heavy metal concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (NOAA, 1987a). Samples from the same sites, with the exception of the site off Oakland, were again analyzed in 1985. The overall mean chromium concentration for the 2-year period was 336 ppm with a standard deviation of 167 ppm and a range of 131 ppm to 769 ppm. The site means ranged from 196 ppm at the Oakland site to 522 ppm at the San Pablo Bay site (Figure 50). The single sample with the lowest chromium concentration (131 ppm) was from the Hunters Point site in 1985, while the sample with the highest chromium concentration (769 ppm) was from the San Pablo Bay site also in 1985. In both 1984 and 1985, samples from a site in Bodega Bay, an area minimally influenced by anthropogenic activities, were also analyzed for heavy metal concentrations. The 2-year mean for the site was 350 ppm, with a range of from 117 to 685 ppm. The San Pablo Bay site was significantly different than the Oakland and Southampton Shoal (259 ppm) sites (p=0.05). The Bodega Bay site (4 ppm) was not significantly different than any of the San Francisco Bay sites (p=0.05).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) survey at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Chapman et al., 1986). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean chromium concentration in the sediments, based on three samples per site, was 101 ppm with a range of 72 to 146 ppm (Figure 50). The Islais Creek site (130 ppm) was significantly different than the San Pablo Bay (84 ppm) and Oakland sites (90 ppm) (p=0.05).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for heavy metal concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba

Buena Island, and near the San Mateo Bridge. In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987). The analyses were carried out on samples of the upper 1 cm of sediment. The overall mean chromium concentration for the sites in the Bay, based on three samples per site, was 181 ppm with a range of 170 to 210 ppm (Figure 50). The individual site means ranged from 170 ppm at the San Mateo Bridge to 193 ppm at Semple Point; the Tomales Bay mean was 230 ppm (Figure 52). The Tomales Bay site was significantly different than the four sites in the Bay (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 241 ppm. Statistical analyses indicated that the East San Pablo Bay site (522 ppm) was significantly different than the West San Pablo Bay (84 ppm), Oakland (143 ppm), and Islais Creek (130 ppm) sites; and in addition, the west San Pablo Bay site was significantly different than the Hunters Point (297 ppm) and Bodega Bay (350 ppm) sites (p=0.05). Figure 52 displays the mean concentra- tions from the NS&T Program data for the sites sampled in 1984 through 1986.

(2) Temporal Trends

No broad-scale, long-term monitoring of chromium concentrations has been conducted in the Bay. Rather, data have been collected in various parts of the Bay in many separate studies. During the 17-year period over which data have been compiled, chromium concentrations in the sediments of the Bay have fluctuated from year to year, but have displayed no long-term trends. Figure 50 compares the means by study and year to the grand mean. Despite these yearly fluctuations, no long-term trend of increasing or decreasing concentrations of chromium throughout the Bay are apparent. Because of the variability in chromium concentrations from sample to sample, the yearly fluctuations may be simply due to within-site patchiness and the selection of individual stations where samples were taken each year. Some studies were performed in peripheral areas and others were conducted mainly in the basins of the Bay.

The only data set which extended over several years at the same sites, was from the SBDA study in the southern end of south Bay. From January 1982 through April 1986, the SBDA sampled two sites located in the south Bay basin and two sites in peripheral areas on a quarterly basis. The mean chromium concentrations in the surficial sediments were around 25 ppm at the beginning of the study period, decreased to around 14 ppm in January and April 1983, and then rose sharply to 51 ppm in July 1983. They increased further to 72 ppm in January 1984. After January 1984, chromium concentrations fluctuated between about 15 ppm and 50 ppm until July 1986 when the highest monthly concentration (98 ppm) occurred (Figure 53).

When the yearly mean chromium concentrations of the NOAA NS&T Program data from all the sites were compared for 1984 through 1986, 1984 was significantly different than 1985 and 1986 (p=0.05). The means for the 3 years were, 367 ppm in 1984, 198 ppm in 1985, and 181 ppm in 1986. While these data appear to indicate a decreasing trend in chromium contamination, the sites sampled were different each year and the time span involved was too short to draw any concluisions. Also, when just the Benthic Surveillance Project yearly means for 1984 (367 ppm) and 1985 (295 ppm) were compared, there was no significant difference between the 2 years.

B. Biota

Chromium concentrations have been measured in fish and bivalves by 12 surveys since 1971 (Table 2). Pooling the data from 288 samples of mussels (*Mytilus edulis, M. californianus*) analyzed between 1971 and 1986 for chromium content shows the mean chromium concentration for San Francisco Bay to have been 2.72 ppm, with a median of 2.2 ppm (Table 22). Chromium concentrations in San Francisco Bay mussels have ranged from less than 0.1 to14.8 ppm. South Bay and some of its peripheral areas produced high mean chromium levels in mussels. However, since each basin is unevenly represented in the calculation of these means, the results must be interpreted with caution. Specifically, south Bay has been sampled frequently, whereas only one data point was found for the Suisun Bay/Carquinez Strait basin. The grand mean chromium concentration in San Francisco Bay mussels exceeds that from the reference areas (Tomales Bay and Bodega Head) by factors of 3.9 and 1.3, respectively. The means and ranges in chromium concentrations observed in studies of mussels are summarized in Figure 54 and compared to the historical grand mean for the Bay.

(1) Geographic Trends

Sampling of clams (*Tapes semidecussata* or *Mya arenaria*) by the U.S. EPA (Shimmin and Tunzi, 1974) in 1972 showed highest chromium concentrations at Tara Hills in San Pablo Bay (between 1.7 and 6.6 ppm wet weight--approximately 15 to 59 ppm dw). Clams from sites in the central Bay also contained elevated chromium concentrations (3 to 32 ppm dw). Clams from south Bay had concentrations of 2.6 to 10 ppm at most sites and 23 ppm at a Bayview Park site.

Wyland (1975) sampled resident mussels (*Mytilus edulis*) from Tomales Bay and three sites in San Francisco Bay in 1974. Mean chromium concentrations in mussels from Tomales Bay (0.16 ppm) and Redwood Creek (0.83 ppm) were both significantly different from concentrations in mussels from Berkeley Marina (7.3 ppm) and Coyote Point (10.1 ppm) ($p=0.05$). The total range in concentrations in the study was from <0.1 to 14.8 ppm (Figure 54).

Levels of chromium in mussels (*Mytilus edulis*) sampled in 1976 at mostly basin sites from around the Bay (Risebrough et al., 1978) were highest at channel buoy 2 in southern San Francisco Bay (4.9 ppm). Mussels from the Bay Bridge, San Mateo Bridge, and Redwood City Harbor contained more than 4 ppm chromium. Many samples contained chromium levels below high detection limits (3 or 4 ppm). The total range in concentrations was from 1.5 to 4.9 ppm (Figure 54).

In 1980, the sampling of bay mussels (*Mytilus edulis*) from 12 sites by the California Mussel Watch (Hayes et al., 1985) and by McCleneghan et al. (1982) showed highest levels of chromium to be detected at Davis Point and Point Pinole in San Pablo Bay (7.5 and 5.3 ppm, respectively). Mussels from Dumbarton Bridge contained 2.7 ppm chromium. Mussels from all the other sites had 0.7 to 1.3 ppm chromium. Mussels sampled by McCleneghan et al. (1982) from peripheral areas did not contain significantly higher levels of chromium than those from basin areas. Sampling of Japanese littleneck clams (*Tapes japonica*) in 1980 by McCleneghan (1982) and Kinney and Smith (1982) showed highest chromium levels (27.75 ppm) in San Leandro Creek (Figure 55). Lowest chromium concentrations (1.7 to 3.9 ppm) were detected in clams from parts of the central Bay. No significant differences occurred between sites ($p=0.05$), except for the following: the San Leandro Bay site (27.7 ppm) exceeded both the Point Isabel site (1.3 to 5.5 ppm) and the Berkeley site (3.0 ppm); and the Point Isabel site exceeded the Berkeley site ($p=0.05$).

The NS&T Program (NOAA, 1987a) analyzed chromium in the livers of starry flounder (*Platichthys stellatus*) or white croaker (*Genyonemus lineatus*) from four sites in San Francisco Bay and a site in Bodega Bay in 1984 (Figure 56). These analyses showed highest levels of chromium in liver tissue of starry flounder from Southhampton Shoal (0.25 ppm). Lowest chromium levels were found in liver tissue of starry flounder caught off Hunters Point (0.09 ppm). However, differences between sites were not significant ($p=0.05$). The sites and species sampled by the NS&T Program have apparently not been sampled for chromium in other surveys.

The mean concentrations in transplanted mussels (*Mytilus californianus*) analyzed by California Mussel Watch (Hayes et al., 1985; Hayes and Phillips, 1986, 1987) remained similar to the Bay-wide grand mean in 1980, 1981, 1982, and 1983 (Figure 57). However, in 1983, a sample from Point Davis drove the range for the year up to 6.1 ppm. In 1984, samples from Treasure Island (6.5 ppm), San Mateo Bridge (4.1 ppm), and Dumbarton Bridge (5.2 ppm) effectively increased the annual mean for the data and the range. A sample from Mare Island Strait (*Mytilus edulis*, 7.4 ppm) expanded further the annual range of values in 1985. In 1986, three sites in the Oakland Inner Harbor had transplanted mussels with 3.8 to 5.4 ppm chromium; the concentrations at the other sites ranged from 3 to 4.7 ppm (Figure 57). Mussels transplanted to peripheral areas generally had chromium levels higher than those transplanted to basin sites.

In 1986, the NOAA NS&T Program analyzed chromium in resident *Mytilus edulis* from the San Mateo Bridge, Dumbarton Bridge, and Tomales Bay and *M. californianus* from Bodega Head (Figure 57) (Boehm et al., 1987). Concentrations of chromium in mussels were: 2.0 ppm, 2.1 ppm, 3.2 ppm, and 2.3 ppm, respectively. Chromium concentrations in mussels from Tomales Bay were significantly different than those from San Mateo Bridge and Dumbarton Bridge, but not from those at Bodega Head (p=0.05). The sites sampled by the NS&T Program have been sampled by others since 1973. At the San Mateo Bridge, Hayes et al., 1985; Hayes and Phillips, 1986, 1987; and Risebrough et al., 1978 detected a mean chromium level of 2.9 ppm (with a range of 1.8 to 4.5 ppm) in mussels sampled between 1976 and 1985. The NS&T Program detected 2 ppm in mussels from a nearby site. At the Dumbarton Bridge, Hayes et al., 1985; Hayes and Phillips, 1986, 1987; and Risebrough, 1978 detected a mean level of 3.1 ppm (with a range of 1.6 to 5.2 ppm), while the NS&T Program detected 2.1 ppm. At Bodega Head, Hayes et al., 1985 and Hayes and Phillips, 1986, 1987 detected a mean level of 1.9 ppm in mussels sampled between 1976 and 1986, while the NS&T Program found 2.3 ppm in mussels. In Tomales Bay, Anderlini et al., 1975b; Wyland, 1975; Hayes et al., 1985, and Hayes and Phillips, 1986, 1987 found a mean level of 0.45 ppm (with a range of from less than 0.1 to 2.4 ppm) in mussels, while the NS&T Program detected 3.2 ppm in mussels sampled nearby.

(2) Temporal Trends

Clams were resampled in 1972, 1975, and 1980 at two sites in San Francisco Bay. Clams (*Tapes spp.*) from Albany Hill and nearby Point Isabel showed apparent declines (from 32 ppm to <6.9 ppm to 1.4 ppm) in chromium concentrations, but chromium levels in clams sampled at Foster City have remained near 3 to 4 ppm between 1972 and 1980 (Shimmin and Tunzi, 1974; Girvin et al., 1975; McCleneghan et al., 1982).

Resident mussels (*Mytilus edulis*) have been resampled at four sites since 1975. Sampling at Foster City and nearby on the San Mateo Bridge at Redwood Creek (and at two sites nearby), and at the Dumbarton Bridge showed no apparent changes in chromium levels since 1975 (Girvin, 1975; Hayes et al., 1985; Boehm et al., 1987). Resident mussels (*M. californianus*) from Bodega Head have been monitored for chromium since 1977 (Hayes et al., 1985; Hayes and Phillips, 1986, 1987). There has been no significant change in concentrations between years (p=0.05).

Transplanted mussels (*M. californianus*) have been resampled at eight sites in San Francisco Bay since 1979 (Figure 58). No major changes in concentration have occurred during the sampling periods. A slight dip in concentrations apparently occurred in December 1982 at many of the sites. Chromium concentrations may have increased slightly since 1980 at the Point Pinole, Redwood Creek mouth, Richmond Bridge, and the San Mateo Bridge sites.

C. Summary

Like many other trace metal concentrations, chromium concentrations in the sediments of San Francisco Bay and its environs display a small-scale patchiness and a large-scale homogeneity. This pattern is illustrated in Figure 50, where chromium concentrations for individual samples ranged from 8 to 769 ppm (a difference of 96 times), but mean concentrations for each study ranged from 25 to 367 ppm (a difference of 15 times). The mean concentrations for the studies exceeded 200 ppm in three instances: in samples analyzed by Serne and Mercer in 1973 and the two years of Benthic Surveillance Project sampling, 1984 and 1985.

The means, standard deviations, medians, and ranges of chromium concentrations in sediments in the four basins and selected peripheral areas based on data from all the studies compiled for this report are listed in Table 23. It also includes the number of samples taken at each area and the years in which sampling took place. While the table orders the areas from highest to lowest mean, any comparisons of areas must be done with extreme caution because of differences in sampling and analytical methodologies, time of sampling, and number of samples taken at each area. Possibly the most significant statistics in Table 23 are the ranges that show a high degree of overlap for all the areas sampled, both basins and peripheral areas. The grand mean for the Bay (89 ppm, Table 21) is exceeded by the mean concentrations for the two reference sites, Bodega Bay (350 ppm) and Tomales Bay (230 ppm), by factors of 3.9 and 2.6, respectively.

Generally, chromium concentrations in San Pablo Bay sediments have been considerably higher than in other parts of the Bay. Some individual samples from Mare Island Strait, Islais Creek, south Bay, central Bay, and Oakland Outer Harbor have had high concentrations, also. However, because of the sporadic sampling for chromium contamination, both geographically and temporally, no clear patterns of chromium distribution can be determined. The high chromium concentrations at the two reference sites suggest that a major portion of chromium in the sediments of the San Francisco Bay area may be of geologic origin.

Chromium appears to be relatively uniformly distributed among biota in the Bay. The respective means and medians in concentrations in mussels among the basins and major peripheral areas are relatively similar. Some mussel samples from the Berkeley Marina, Coyote Point, and Oakland Inner Harbor have had high concentrations (elevated by up to a factor of 5.4 times over the Bay-wide grand mean). Mean and median concentrations in the peripheral areas have generally exceeded those in the basins, but by factors of only about 2. Except when mussel samples were collected in the above three areas, the mean concentrations for any study have generally been similar to the Bay-wide grand mean. The ranges observed in most of the studies have included the grand mean. Some historical data for clams have indicated that sites in San Leandro Bay, near Bayview Park in south Bay, near Tara Hills in San Pablo Bay, near Albany Hill in central Bay, and in Richardson Bay have had high chromium concentrations. No major site-to-site differences in chromium concentrations in fish have been observed.

No significant temporal trends in chromium concentrations in biota are apparent for the sites sampled in the Bay. Concentrations may have decreased since 1972 at the Albany Hill/Point Isabel sites. However, since data from this area are from only three sampling periods, and two nearby (but different) sites and two laboratories, this apparent trend may not be real. Concentrations may have increased slightly at the Point Pinole, Redwood Creek mouth, San Mateo Bridge, and Richmond Bridge mussel watch sites since 1980.

Historical mean concentrations of chromium in sediments sampled from 1972 through 1986 in San Francisco Bay are compared in Figure 59 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper-case print. The NS&T Program sites are in lower-case iprint. Those from the 1984 Benthic Surveillance Project are designated by "BS" after the site name; those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold lower-case print. The overall historical mean concentration for the Bay (89 ppm) ranked relatively low compared to the NS&T Program sites. The means for the central Bay and south Bay basins and all peripheral sites also ranked low. However, the mean for the San Pablo Bay basin was relatively high, exceeded only by a 1984 Benthic Surveillance sites in San Pablo Bay and off Hunters Point. Among the NS&T Program sites, six ranked in the top ten, including the two reference sites.

The historical mean concentrations of chromium in mussels collected in San Francisco Bay from 1972 to 1986 are compared in Figure 60 with means from three samples of mussels each from NS&T Program Pacific Coast sites sampled in 1986. The historical areas are listed in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located in the Bay are listed in bold print. The means for the Bay overall and its major basins were elevated somewhat relative to 1986 means for the Pacific Coast sites. The two NS&T Program Mussel Watch sites in the Bay ranked 24th and 25th among the 1986 data. The Tomales Bay and Bodega Head sites, ranked 6th and 18th, respectively.

Table 21. Bay-wide means, standard deviations, medians, and ranges of chromium concentrations in surficial sediments of San Francisco Bay based on data collected by many investigators from 1971 through 1987 from the four basins and peripheral harbors and waterways (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	89	96	63	8-769	396
BASINS	108	129	51	9-769	140
PERIPHERY	80	70	66	8-534	256

Table 22. Means, medians, and ranges in concentration of chromium in mussels (Mytilus edulis and Mytilus californianus) collected by many investigators in 1971-1986, in basins and periphery of San Francisco Bay (ppm dw).

AREA/SITE	MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY	<4	-	-	-	1
SAN PABLO BAY					
BASIN	2.79	1.28	2.15	1.5-6.1	16
PERIPHERAL-MARE ISLAND STRAIT	5.58	2.53	5.58	3.8-7.4	2
CENTRAL BAY					
BASIN	1.92	1.20	1.90	0.1-6.5	105
PERIPHERAL-RICHMOND HARBOR.	2.95	0.59	2.99	2.3-3.5	4
POINT ISABEL	0.98	0.33	-	0.75-1.22	2
BERKELEY MARINA	6.85	4.50	5.50	2.9-14.7	12
ALL PERIPHERAL	5.33	4.29	3.45	0.8-14.7	18
SOUTH BAY					
BASIN	3.33	2.67	2.50	0.3-14.8	96
PERIPHERAL-ISLAIS CREEK	<6.9	-	-	-	1
NEWARK SLOUGH	2.40	-	-	-	1
ALAMEDA YACHT HARBOR	4.35	0.45	-	4.03-4.66	2
OAKLAND INNER HARBOR	3.46	2.38	4.18	<0.1-5.4	4
OAKLAND OUTER HARBOR	<3.0	-	-	-	1
BAYSHORE LAGOON	0.66	0.23	-	0.50-0.83	2
PALO ALTO YACHT HARBOR	2.50	0.27	2.60	2.2-2.7	3
REDWOOD CREEK	1.90	1.26	2.00	<0.1-4.4	32
BELMONT SLOUGH	2.60	-	-	-	1
ALVISO SLOUGH	5.20	-	-	-	1
ALL PERIPHERY	2.17	1.41	2.20	0.5-5.4	47
ALL SAN FRANCISCO BAY	2.72	2.30	2.20	0.1-14.8	288
TOMALES BAY	0.71	1.11	<0.1	0.7-3.9	28
BODEGA HEAD	2.05	1.11	1.73	0.9-6.6	23

Table 23. Means, standard deviations, medians, and ranges of chromium concentrations in the surficial sediments of San Francisco Bay for three basins and selected peripheral areas based on data collected by many investigators from 1971 through 1987, ordered from highest to lowest by mean (ppm dw).

AREA	YEARS SAMPLED	MEAN	S D	MEDIAN	RANGE	NO. of SAMPLES
SAN PABLO BAY	73, 84-86	280	219	190	33-769	17
CHINA BASIN	79	158	12	158	145-173	4
MARE ISLAND STRAIT	71-73	153	117	91	62-387	28
ISLAIS CREEK	71, 79, 85	140	152	118	8-534	11
RICHMOND HARBOR	72, 73	123	39	123	67-192	7
REDWOOD CITY HBR	71-73	91	58	82	20-208	11
SOUTH BAY	71, 79-86	84	86	48	9-417	74
CENTRAL BAY	71, 73, 80, 81, 84-86	81	94	44	13-383	48
GALLINAS CREEK	81	79	36	75	29-170	27
OAKLAND OUTER HBR	72, 73, 80, 81	73	62	63	18-291	23
SAN LEANDRO BAY	80-81	63	26	61	25-120	15
CASTRO CREEK	81	61	26	63	16-120	43
CORTE MADERA	81	60	22	57	28-110	24
BERKELEY MARINA	80-81	52	12	46	36-75	15
COYOTE CREEK	82-86	41	25	32	13-100	20
GUADALUPE SLOUGH	82-86	38	27	26	11-120	20
BODEGA BAY	84-85	350	197	337	117-685	6
TOMALES BAY	86	230	0	230	230-230	3

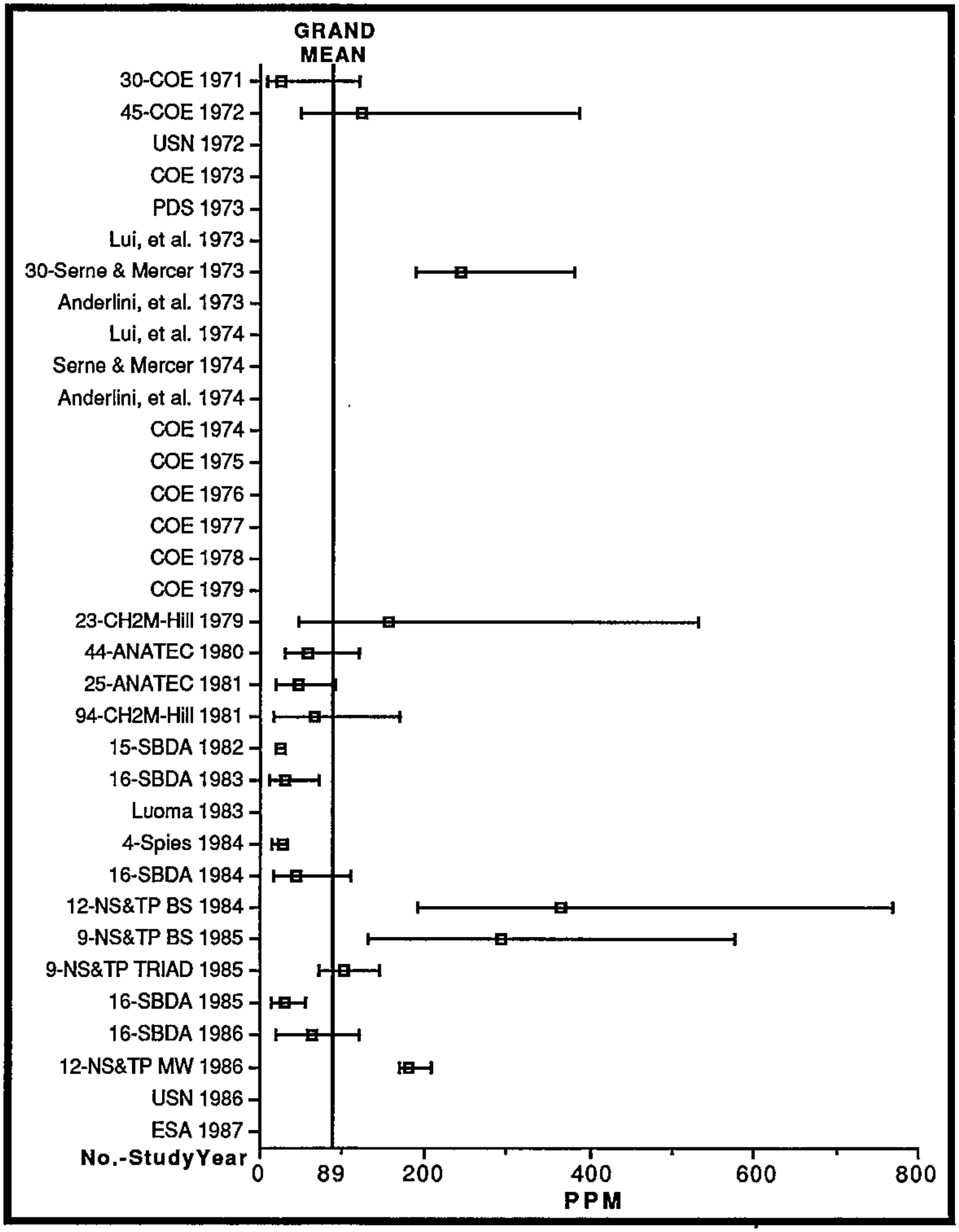


Figure 50. Mean concentration of chromium in the surficial sediments of San Francisco Bay by study and year compared to the grand mean for the Bay (ppm dw) (No.=number of samples, bars represent the range).

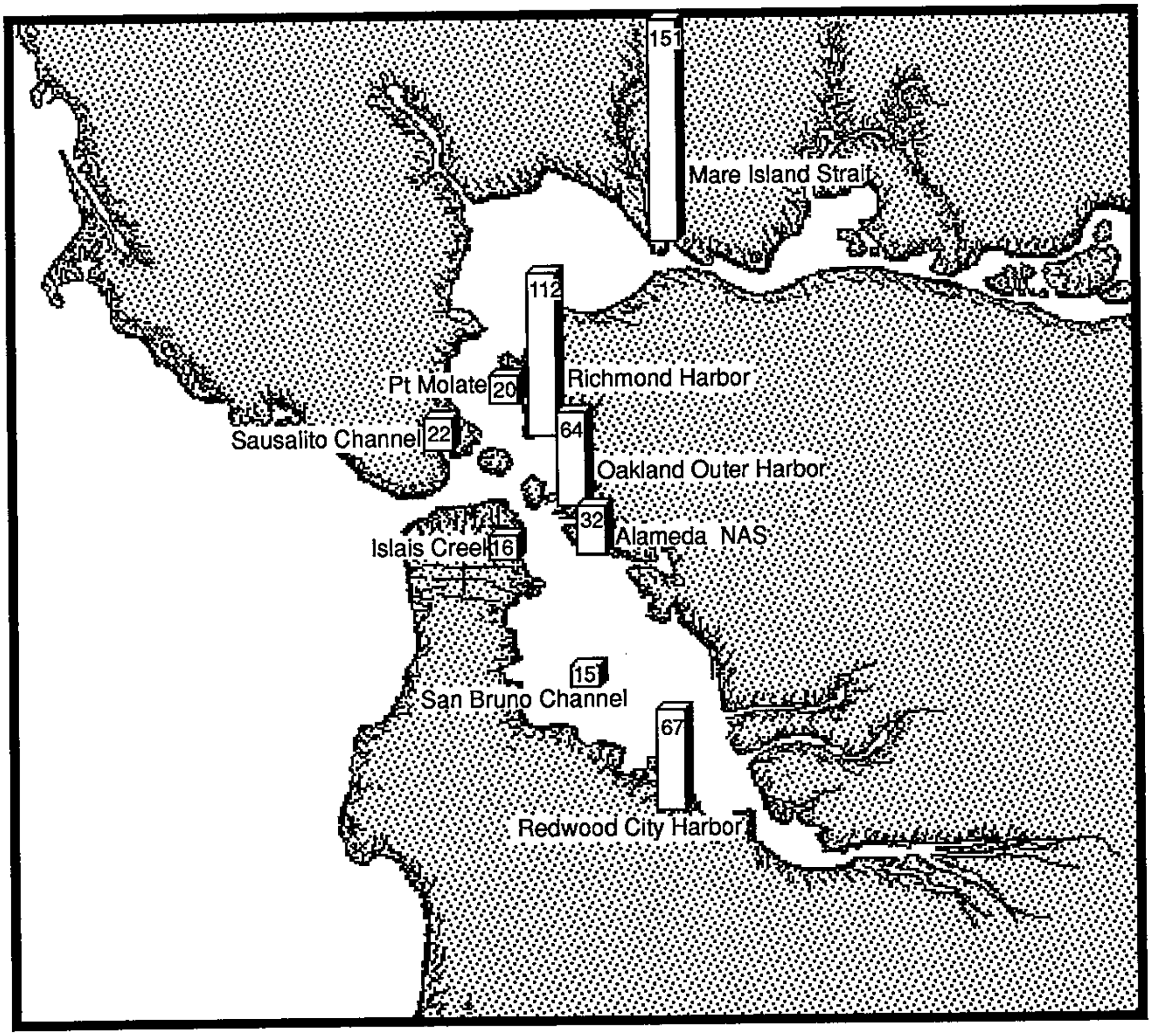


Figure 51. Mean chromium concentrations in sediments, in ppm dw, for 1971-72 based on dredging studies (COE, 1979b).

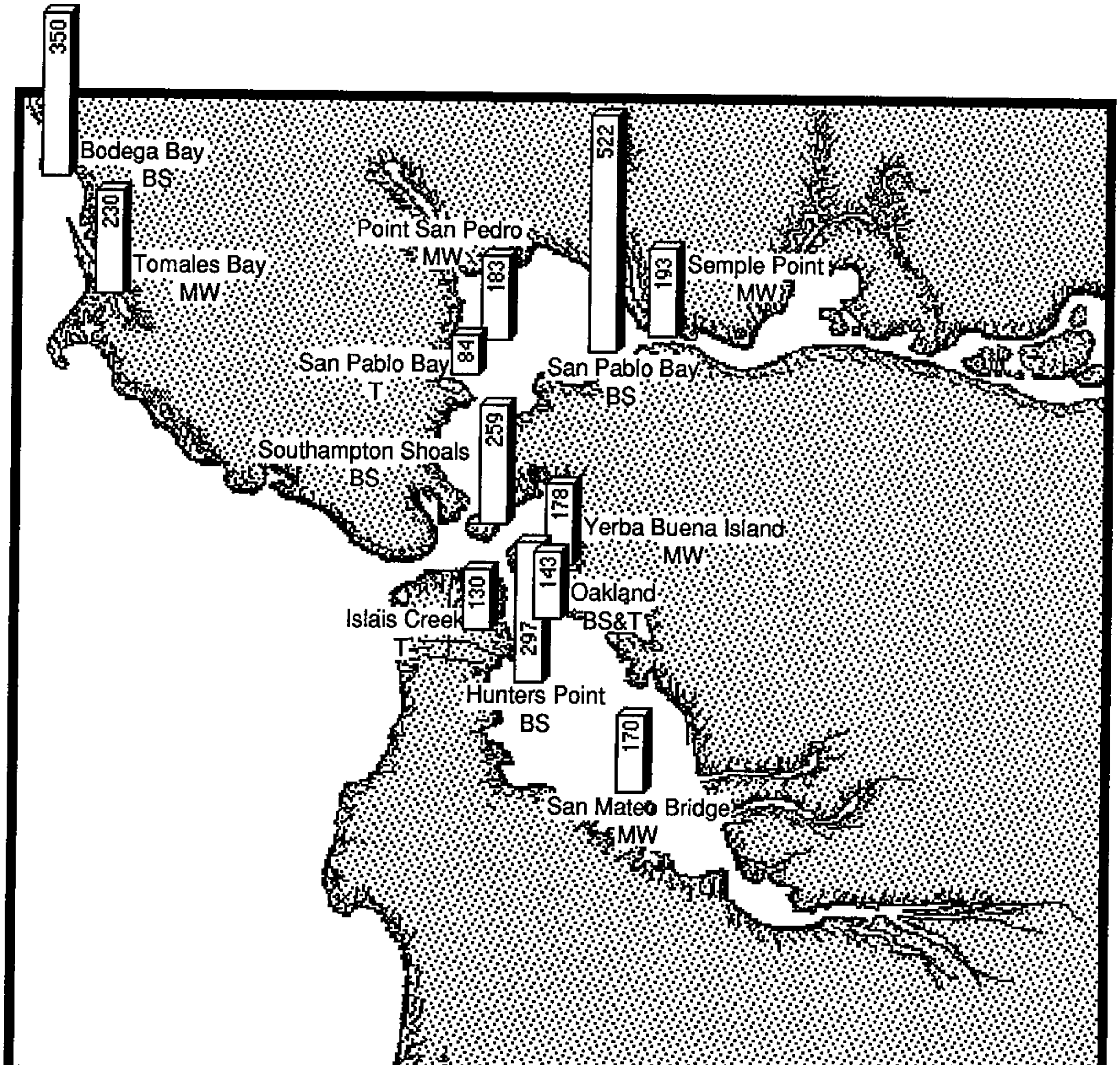


Figure 52. Mean chromium concentrations in the surficial sediments for 1984-86, in ppm dw, based on NOAA NS&T Program data (BS=Benthic Surveillance, MW=Mussel Watch and T=Sediment Quality Triad study) (NOAA, 1987a,; Boehm et al., 1987; Chapman et al., 1986) .

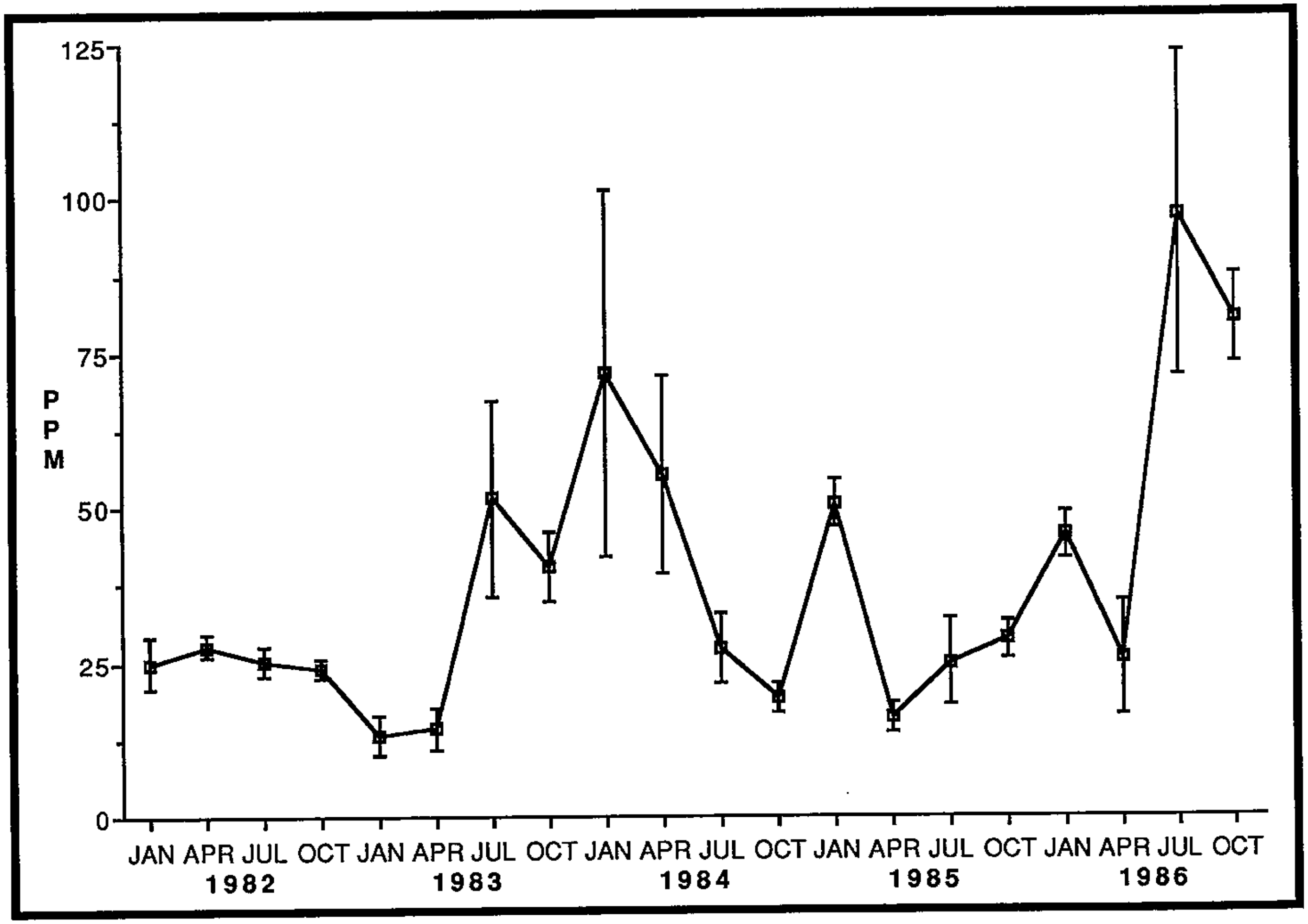


Figure 53. Monthly mean chromium concentration in the surficial sediments at the four sites in the southern end of south Bay sampled by the SBDA from 1982 through 1986 (bars represent one standard deviation) (Stevenson et al., 1987).

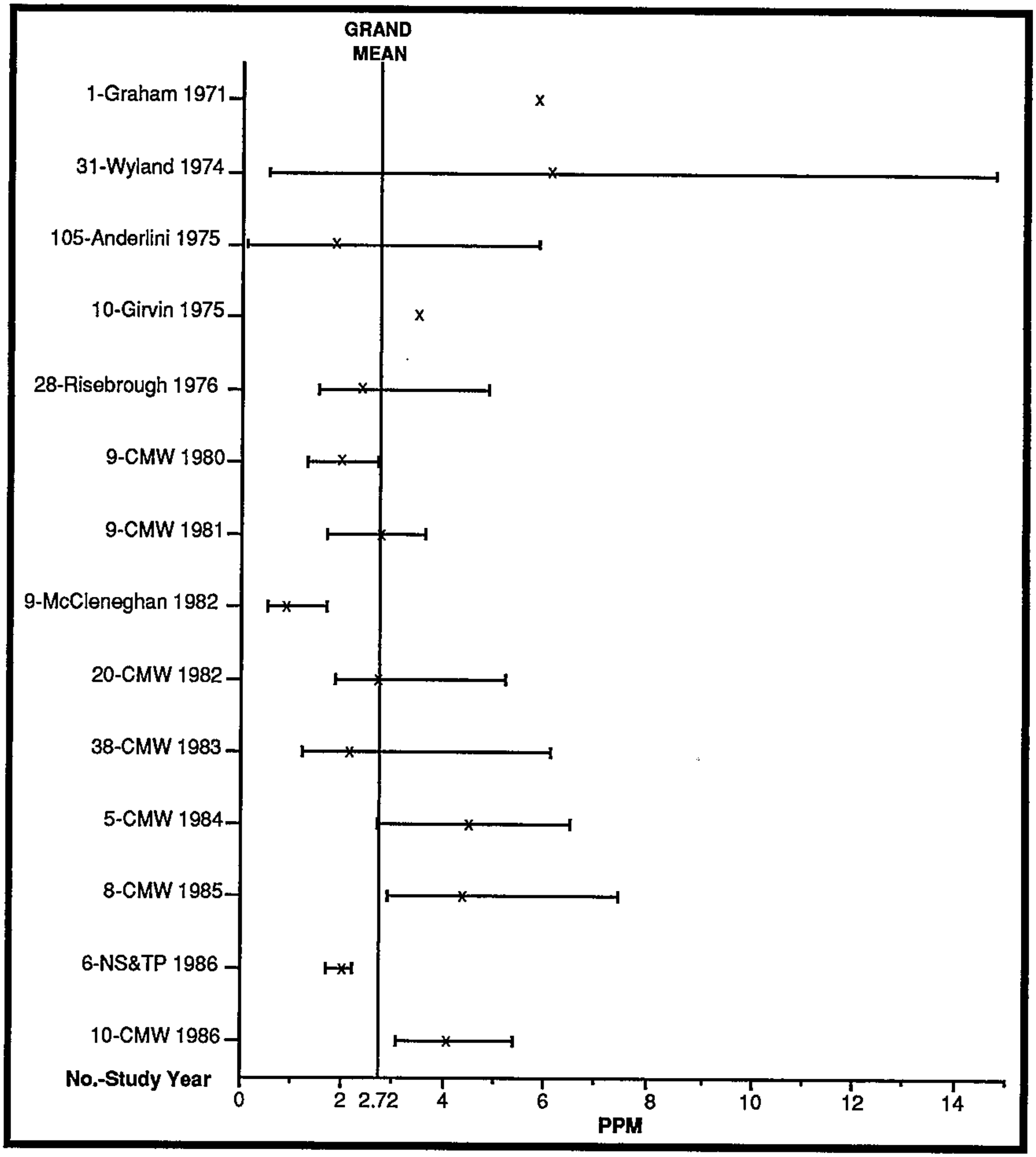


Figure 54. Mean concentration of chromium in mussels (*Mytilus edulis* or *M. californianus*) by study and year in ppm dw (No. =number of samples,bars represent the range).

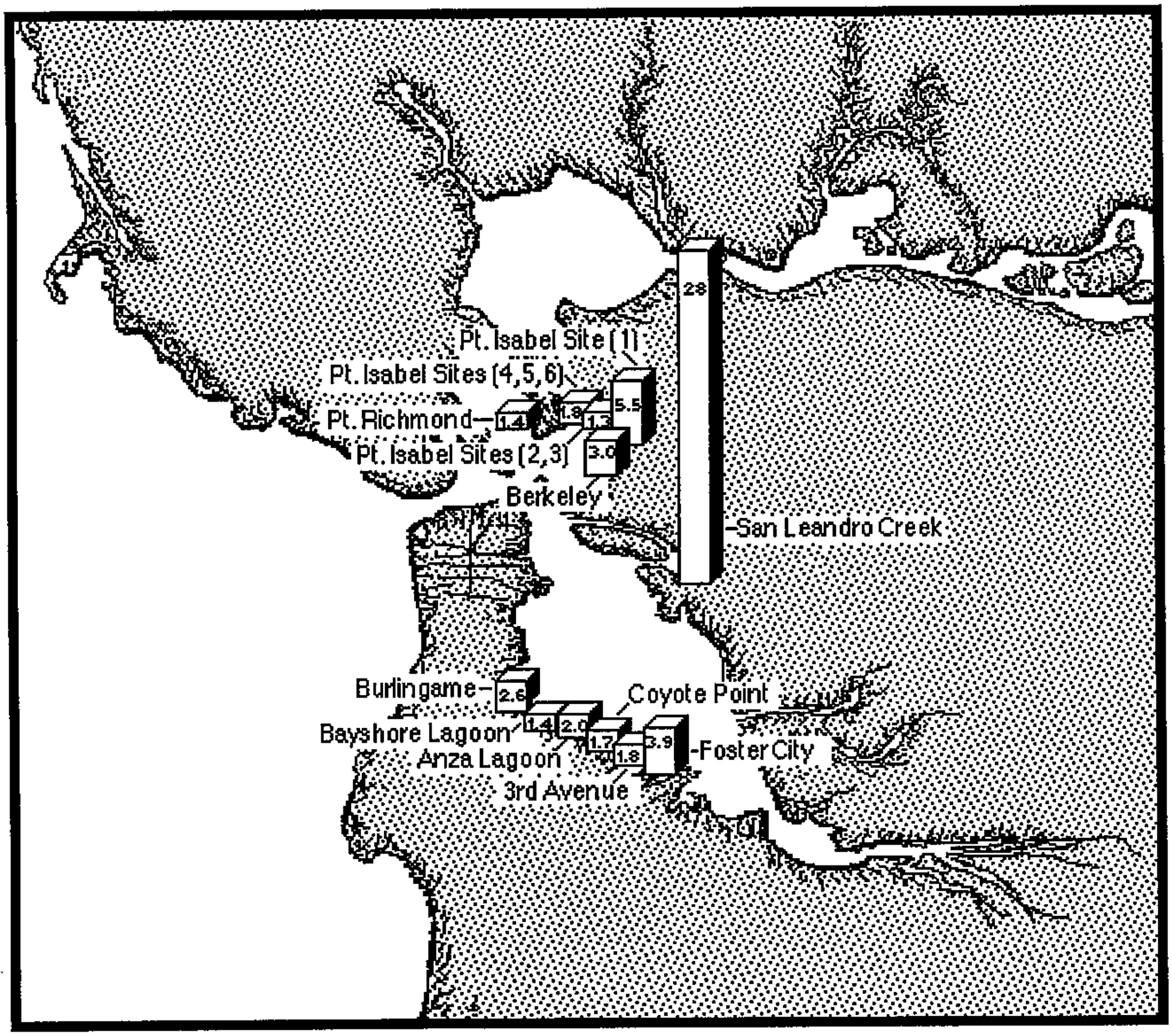


Figure 55. Chromium concentrations in Japanese littleneck clams (Tapes japonica) in 1980 (ppm dw) (McCleneghan et al., 1982; Kinney and Smith, 1982).

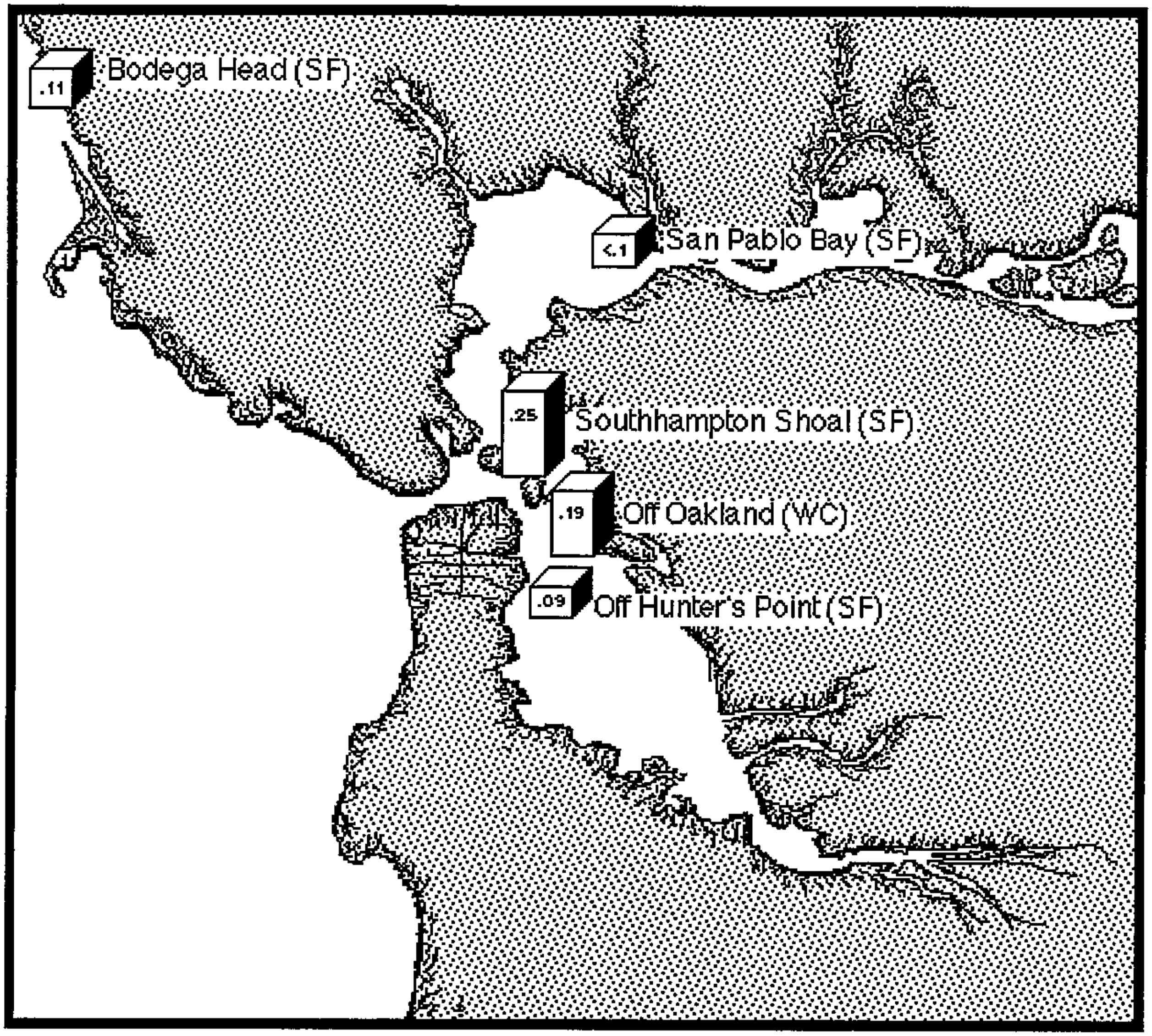


Figure 56. Chromium in liver tissue of starry flounder (SF), Platichthys stellatus, and white croaker (WC), Genyonemus lineatus, sampled in 1984 (NOAA, 1987a).

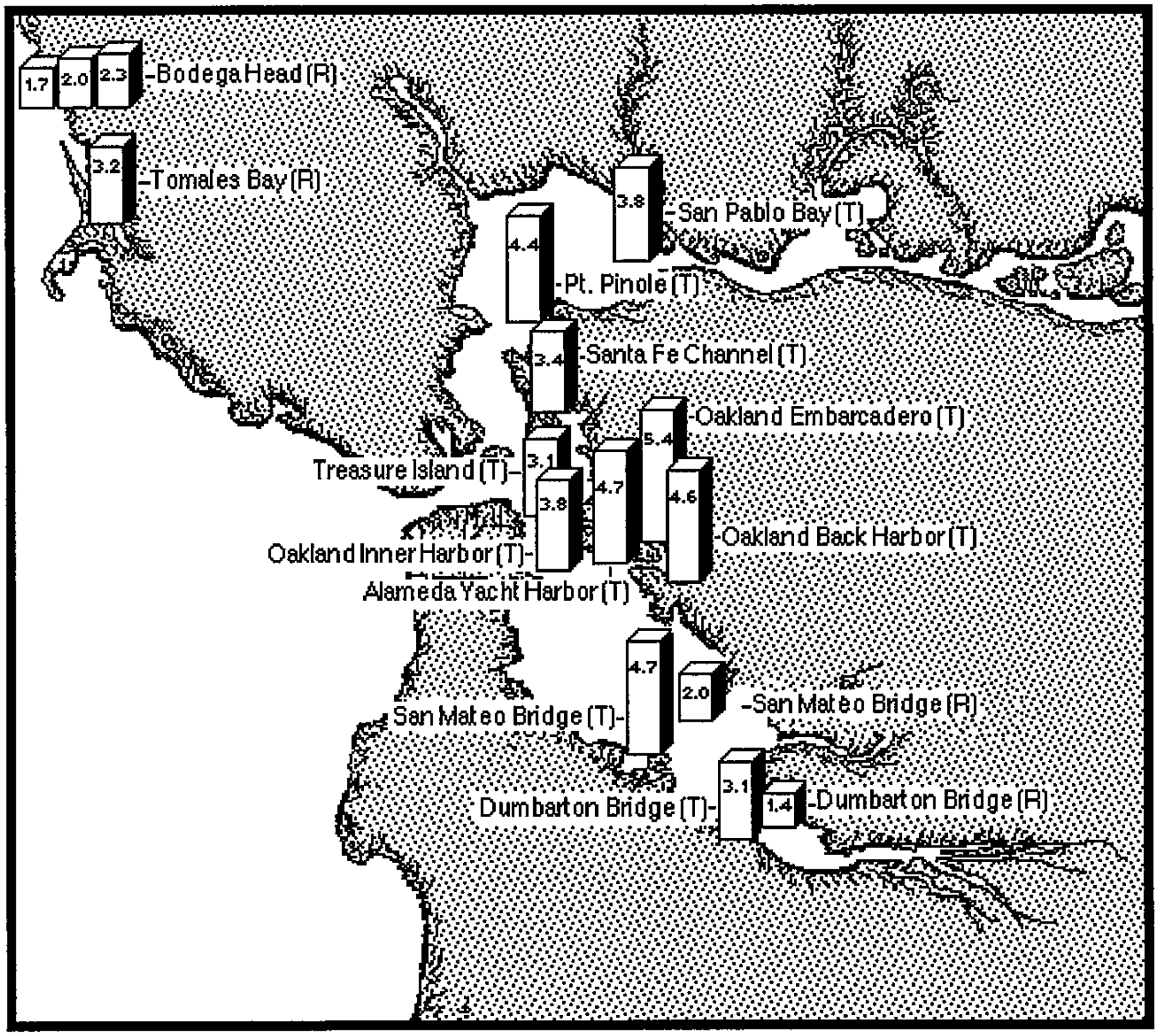


Figure 57. Chromium in transplanted (T) coastal mussels (M. californianus) and resident (R) bay mussels (M. edulis) sampled in 1985-86 by CMW and NS&T Program (Hayes and Phillips, 1987; Boehm et al., 1987).

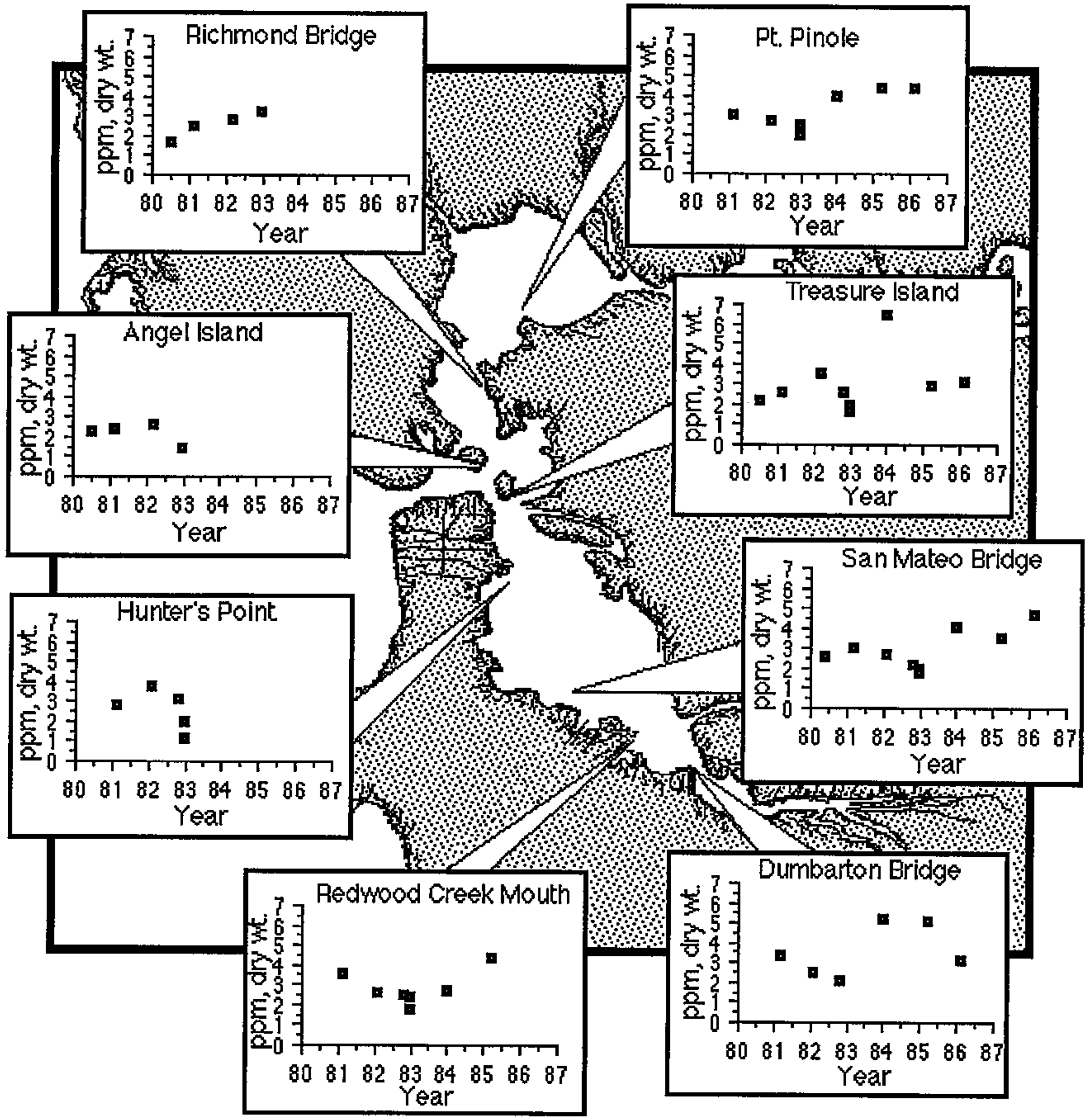


Figure 58. Temporal trends in chromium concentrations in transplanted mussels (M. californianus)1980-86 (Hayes et al., 1985; Hayes and Phillips, 1986, 1987).

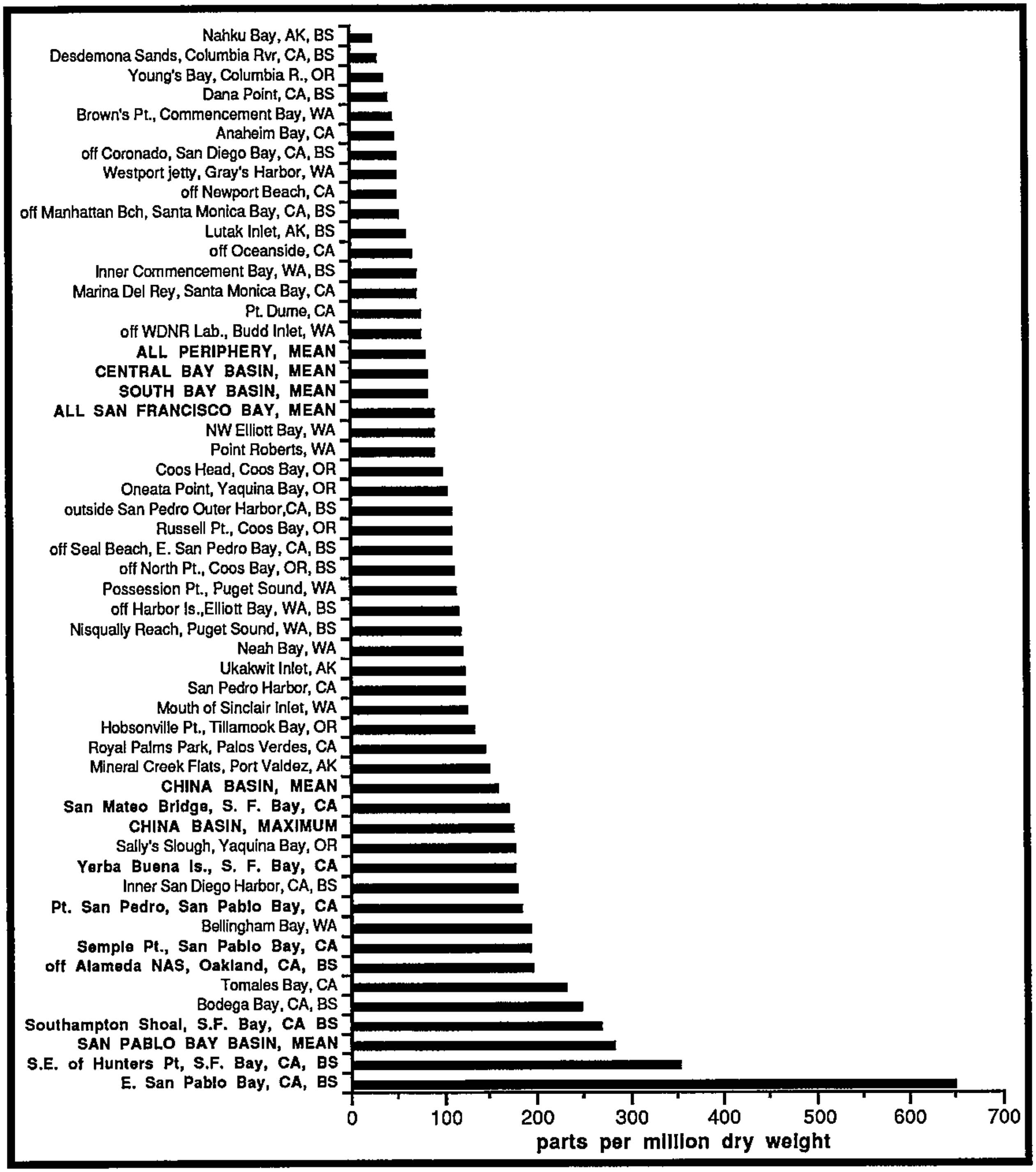


Figure 59. Comparison of chromium concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Tables 21, 23), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name) .

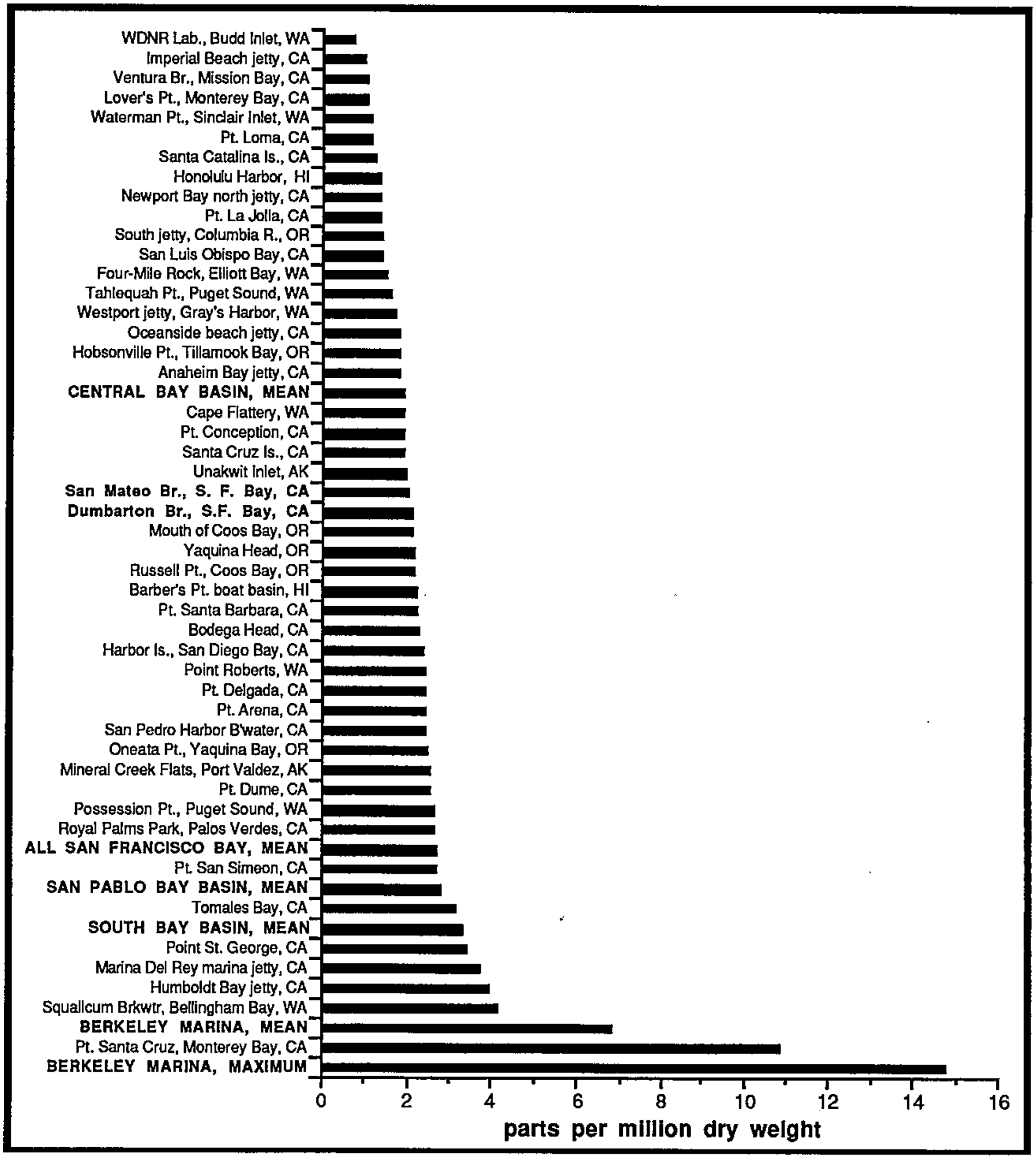


Figure 60. Mean chromium concentrations in resident mussels (Mytilus edulis, M. californianus) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1972-1986) data for San Francisco Bay (from Table 22). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

GEOGRAPHIC AND TEMPORAL TRENDS IN SILVER CONTAMINATION

A. Sediments

Data on the concentration of silver in the surface sediments of San Francisco Bay and its environs have been compiled sporadically by several investigators during the period 1973 through 1987 (Table 1). Based on 336 samples collected throughout the system, the grand mean concentration of silver in San Francisco Bay sediments for the last 15 years was 1.13 ppm with a standard deviation of 1.52 ppm and a range of from less than 0.01 to 16 ppm (Table 24). However, 35 of the samples analyzed during the SBDA study were below detection limits, probably due to a problem in analytical techniques and not to low silver concentrations (Stevenson et al., 1987). When these samples are excluded from the calculations, the grand mean for silver becomes 1.26 ppm. The majority of the silver values (60 percent) were less than 1 ppm (40 samples had silver concentrations below detection limits including those of the SBDA study), while 38 percent were between 1 and 5 ppm. The remaining five samples (1.5 percent) had concentrations from 8 to 16 ppm; the two samples with the highest levels were from China Basin, while the other three were from Islais Creek. The median value was 0.58 ppm. The ranges and means in silver concentrations reported in the 17 studies in which silver was quantified are summarized in Figure 61 and compared to the grand mean for the Bay.

(1) Geographic Trends

As part of the COE's intensive dredging study, Anderlini et al. (1975a) analyzed 58 sediment samples from 13 sites in Mare Island Strait during five sampling periods from October through December 1973. Sediment samples from six of the sites were also analyzed four times from February through April 1974. The overall mean level of silver found in the sediments was 2.12 ppm with a standard deviation of 0.91 ppm and a range from 0.5 to 4.90 ppm (Figure 61). Ten of the sites were paired down the length of the strait, two were paired off the southern tip of Mare Island, and the thirteenth site was located at the disposal site off the southern end of Mare Island. When the mean silver concentrations were calculated for each pair of sites, they ranged from 1.45 ppm for the pair of sites at the mouth of the strait to 2.45 ppm at the pair of sites farthest up the strait. While there was a tendency for silver concentrations to increase moving up the strait, there were no significant differences between any of the pairs of sites ($p=0.05$).

CH2M-Hill prepared a report in 1979 for the City and County of San Francisco on the effects of untreated sewage overflows on the eastern portion of south San Francisco Bay (CH2M-Hill, 1979). Sediments from the upper 10 to 13 cm at 23 sites between China Basin and Brisbane Lagoon were analyzed for silver. Replicate samples (two to five) were collected at each site. The overall mean concentration of silver at the 23 sites was 2.09 ppm with the means of the individual sites ranging from 0.35 to 16 ppm (Figure 61). The highest silver concentration (16 ppm) was found at the head of the China Basin and decreased at each site from the head to the mouth of the basin; the silver concentration at the site at the mouth of the basin was 0.9 ppm. The same pattern was apparent in Islais Creek Waterway where the silver concentration at the head of the waterway was 9 ppm and that at the mouth was less than 0.7 ppm. Eight of the sites had silver concentrations below the detection limit of 0.7 ppm.

ANATEC and Kinnetic Laboratories conducted a monitoring program for the East Bay Municipal Utility District from 1980 to 1981 (Kinney & Smith, 1982). They analyzed 69 samples of the upper 10 cm of sediment from six areas (Oakland Outer Harbor, San Leandro Bay, off the Stege Plant, Berkeley Flats, Berkeley Marina, and west of Alameda Island). The overall mean silver concentration for the study was 0.67 ppm with a standard deviation of 0.58 ppm and a range of from less than 0.7 to 4 ppm (Figure 61). The means for the individual sampling areas ranged from a low of 0.5 ppm at the Alameda site to a high of 1.1 ppm in Oakland Outer Harbor. There were no significant differences between any of the sampling areas ($p=0.05$).

Luoma et al.(1984) collected and analyzed 29 samples of the oxidized layer of sediment from 10 sites in Suisun Bay. The overall mean silver concentration for the study was 0.15 ppm with a standard deviation of

0.09 ppm and a range of from 0.03 to 0.39 ppm (Figure 61). The means for the indiviual sites ranged from 0.07 ppm at Roe Island (one sample) to 0.20 ppm at New York Slough (five samples). There were no significant differences between any of the sampling areas (p=0.05).

The SBDA conducted a 5-year monitoring program from 1982 through 1986 at four sites in the southern end of south Bay (Stevenson et al., 1987). They sampled the upper 5 cm of the sediments. Two of the sites were located in the basin of south Bay, one slightly north of Dumbarton Bridge and the other about midway between the bridge and the mouth of Coyote Creek. The other two sites were located in peripheral areas of the Bay, one in Coyote Creek and the other in Guadalupe Slough. The overall mean concentration of silver in the sediments at the four study sites over the 5-year period was 0.57 ppm with a standard deviation of 0.54 ppm and a range of less than 0.1 to 2.1 ppm. However, during the first nine quarterly sampling periods, silver was undetected in all of the samples, probably due to problems in the analytical techniques (Stevenson et al., 1987). When these below-detection-limit values were excluded from the calculations, the overall mean silver concentration became 0.99 ppm with a standard deviation of 0.36 ppm and a range 0.54 to 2.1 ppm. The overall means for the individual sites for the same period ranged from 0.47 to 0.61 ppm; however, when the below detection limit values were excluded, the site means ranged from 0.78 to 1.07 ppm. There were no significant differences between any of the sites during the study period (p=0.05).

In 1986, a study on the potential environmental impact of homeporting the *U.S.S. Missouri* in San Francisco Bay was carried out for the U.S. Navy (U.S. Navy, 1987), followed by a supplemental study in 1987 (ESA, 1987). In 1986, sediment core samples were taken from four sites around the piers of Hunters Point Naval Shipyard and six sites around Treasure and Yerba Buena islands; the upper 12 inches of the cores were analyzed for silver. Two more sites at Hunters Point were sampled and analyzed in 1987 (ESA, 1987). The mean silver concentration of the 12 sites was 1.87 ppm with a range of from 1 to 2.5 ppm. When the data were log-transformed and subjected to an unpaired T-test, the Hunters Point sites (1.65 ppm) and the Treasure Island and Yerba Buena Island sites (2.08 ppm) were significantly different (p=0.05).

In 1984, the Benthic Surveillance Project (BS) of NOAA's NS&T Program began analyzing samples of the upper 1 cm of sediment for heavy metal concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (NOAA, 1987a). Samples from the same sites, with the exception of the site off Oakland, were again analyzed in 1985. The overall mean silver concentration for the 2-year period was 0.29 ppm with a standard deviation of 0.38 ppm and a range of from less than 0.01 ppm to 1.68 ppm. The site means ranged from 0.08 ppm at the Oakland site to 0.45 ppm at the Southampton Shoal site. Five of the twelve samples (two each from Hunters Point and Oakland and one from San Pablo Bay) were below the detection limit (0.01 ppm) in 1984, and the sample with the highest concentration (1.68) was from Southampton Shoal in 1984. In both 1984 and 1985, samples from a site in Bodega Bay, an area minimally influenced by anthropogenic activities, were also analyzed for heavy metal concentrations. The 2-year mean for the site was 0.92 ppm, with a range of from less than 0.01 to 2.66 ppm. There was no significant difference among the Bay sites nor between any of the Bay sites and the Bodega Bay site (p=0.05).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) survey at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Chapman et al., 1986). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean silver concentration in the sediments, based on three samples per site, was 3.38 ppm with a range of 0.9 to 8.6 ppm (Figure 61). The Islais Creek site (6.9 ppm) was significantly different than the San Pablo Bay (1.2 ppm) and Oakland sites (2.0 ppm) (p=0.05).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for heavy metal concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba Buena Island, and near the San Mateo Bridge. In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987). The analyses were carried out on samples of the upper 1 cm of sediment. The overall mean silver concentration for the sites in the Bay, based on three samples per site, was 0.34 ppm with a range of 0.2 to 0.46 ppm (Figure 61). The individual site means ranged from 0.24 ppm at Semple Point to 0.43 ppm at San Mateo Bridge; the

Tomales Bay mean was 0.14 ppm (Figure 62). Within the Bay, Semple Point was significantly different than Yerba Buena and San Mateo Bridge; Tomales Bay was significantly different than all the San Francisco Bay sites (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 0.97 ppm. There was no significant difference among the Bay sites nor between any of the Bay sites and the two reference sites in Tomales and Bodega Bays (p=0.05). Figure 62 displays the mean concentrations from the NS&T Program (MW, Triad, BS) data for the sites sampled in 1984 through 1986.

(2) Temporal Trends

No broad-scale, long-term monitoring of silver concentrations in sediments has been conducted in the Bay. Rather, data have been collected in various parts of the Bay in many separate studies. During the 15-year period over which data have been compiled, silver concentrations in the sediments of the Bay have fluctuated from year to year, but have displayed no long-term trends. Figure 61 compares the means by study and year to the grand mean. Despite these yearly fluctuations, no long-term trend of increasing or decreasing concentrations of chromium throughout the Bay are apparent. Because of the variability in silver concentrations from sample to sample, the yearly fluctuations may be simply due to within-site patchiness and the selection of individual stations where samples were taken each year. Some studies were performed in peripheral areas and others were conducted mainly in the basins of the Bay.

The only data set which extended over several years at the same sites was from the SBDA study in the southern end of the south Bay. From January 1982 through April 1986 the SBDA sampled two sites located in the south Bay basin and two sites in peripheral areas on a quarterly basis. As previously mentioned, from January 1982 through January 1984 the silver concentration in all samples was below detection although these results may have been due to analytical error. From April 1984 through April 1986 the silver concentrations fluctuated between 0.75 and 1.05 ppm, they then increased to 1.30 ppm in July and then to 1.60 ppm in October 1986 (Figure 63). There was no significant difference between any of the sampling periods from April 1984 through October 1986 (p=0.05).

When the yearly mean silver concentrations of NOAA's NS&T Program data from all the sites were compared for 1984 through 1986, 1984 was significantly different than 1985 and 1986 (p=0.05). The means for the 3 years were, 0.28 ppm in 1984, 1.84 ppm in 1985 and 0.34 ppm in 1986. If the 1985 data from the Islais Creek site were excluded, the mean concentration would become 0.83 ppm for 1985. With or without the 1985 Islais Creek site data, the mean silver concentration in 1984 was lower than in 1985 and 1986 (p=0.05).

B. Biota

Silver concentrations have been measured in fish and bivalves by 15 major surveys since 1971 (Table 2). Pooling all data (317 samples) on silver concentrations in mussels (*Mytilus edulis, M. californianus*) analyzed between 1971 and 1986 shows the grand mean silver concentration for San Francisco Bay has been 0.97 ppm, with a median of 0.64 ppm (Table 25). Silver concentrations in San Francisco Bay mussels have ranged from 0.02 to 22.5 ppm. Mean silver concentrations in mussels appear to decrease toward San Pablo Bay. Highest concentrations have been observed in peripheral areas of the south Bay. However, since each basin is unevenly represented in the calculation of these means, the results must be interpreted with caution. Specifically, south Bay has been sampled frequently, whereas only one data point was found for the Suisun Bay/Carquinez Strait basin. The grand mean silver level in San Francisco Bay mussels is elevated above the means from Tomales Bay and Bodega Head by factors of approximately 7 and 5, respectively. The means and ranges in concentrations determined in individual studies of mussels in the Bay are summarized and compared to the Bay-wide grand mean in Figure 64.

(1) Geographic Trends

Clams (*Tapes japonica*) sampled at five sites during 1975 by Girvin et al. (1975) showed highest concentrations of silver in south Bay at Redwood Creek, Foster City, and Coyote Point (14 to 34 ppm). Lowest silver concentrations were found in clams from Albany Hills (2.1 ppm) and Bayview Park (3.3 ppm)

Wyland (1975) analyzed *Mytilus edulis* for silver at sites in Redwood Creek, at Coyote Point, in the Berkeley Marina, and in Tomales Bay in 1974. All but two of the samples had less than the detection limit of 0.05 ppm silver. Two samples at the Redwood Creek site had 3.5 and 13.3 ppm.

Anderlini et al. (1975a) sampled *Mytilus edulis* at many sites in Carquinez Strait, Mare Island Strait, and Tomales Bay. The overall mean for the analyzed samples for the Bay was 0.47 ppm and the range was <0.5 to 1.1 ppm (Figure 64). The site at the Selby Pier in Carquinez Strait had two samples with 0.7 and 1.1 ppm silver. In 1975, Anderlini et al. (1975b) sampled more sites in central Bay for *Mytilus edulis* and found a mean concentration of silver of 1.11 ppm and a range.of 0.2 to 3 ppm (Figure 64). Concentrations at the EBMUD Spoil Disposal and Berkeley Pier sites were not different ($p=0.05$).

In 1976, Risebrough et al. (1978) and the EPA Mussel Watch Program analyzed silver in mussels (*Mytilus edulis*) from 28 sites in San Francisco Bay and a site at Bodega Head. Highest levels were detected in mussels from Redwood City Harbor by Risebrough (1.7 ppm) and on a buoy off Redwood City (1.2 ppm). Silver concentrations at all the remaining sites, including Bodega Head, were very similar (0.1 to 0.7 ppm).

Much lower concentrations were observed in *Mytilus edulis* sampled at 12 sites in 1980 by the California Mussel Watch (Hayes et al., 1985) and by McCleneghan et al., 1982. The highest concentration (1.4 ppm) of silver was detected at a San Mateo Bridge site. Mussels from the other sites in south, central, and San Pablo bays had concentrations ranging from 0.02 to 0.43 ppm. The overall mean concentrations for both studies were well below the grand mean for the Bay (Figure 64). Mussels sampled from sites in south Bay contained slightly higher levels of silver than those from central or San Pablo bays. Japanese littleneck clams (*Tapes japonica*) sampled in 1980 (Figure 65) had highest silver levels at Bayshore Lagoon (7.0 ppm) and off Virginia Street at Berkeley (5.3 ppm) (McCleneghan et al., 1982; Kinney and Smith, 1982). Lowest silver levels were detected in clams from San Leandro Creek (0.64 ppm). Silver levels in clams sampled by Kinney and Smith at San Leandro Bay were significantly lower than those at Point Isabel and Berkeley ($p=0.05$).

The California Mussel Watch determined a mean of 0.3 ppm silver in *Mytilus edulis* and *M. californianus* at nine sites in the Bay in 1980 (Figure 64). In 1981, the same program recorded a concentration of 4.3 ppm in transplanted *M. californianus* at a site in the mouth of Redwood Creek and 1.9 and 2.6 ppm at the San Mateo Bridge and Dumbarton Bridge, respectively. In the following year, the highest concentrations yet recorded for mussels (19.7 and 22.5 ppm) in the Bay were determined in two Redwood Creek samples of transplanted *M. californianus.* Concentrations at a site in San Pablo remained around 0.1 ppm in 1982. In 1983, the concentrations of silver in seven samples from Redwood Creek ranged from 0.5 to 1.5 ppm and averaged 0.85 ppm. The mean and range in concentrations for that study year dropped considerably (Figure 64). California Mussel Watch data for 1984, 1985, and 1986 have remained at or below the grand mean for the Bay. Low silver concentrations (0.06 to 0.23 ppm) were observed in *Corbicula sp.* at eight sites in Suisun Bay and the Delta in 1983 (Luoma et al., 1984).

The NS&T Program (NOAA, 1987a) analyzed silver in the livers of starry flounder (*Platichthys stellatus*) or white croaker (*Genyonemus lineatus*) from four sites in San Francisco Bay and at a site in Bodega Bay in 1984 (Figure 66). These analyses showed highest levels of silver in liver tissue of white croaker taken from off Oakland (0.9 ppm). Lowest silver levels were found in liver tissue of starry flounder from Southhampton Shoals (0.27 ppm) and eastern San Pablo Bay (0.32 ppm). Any differences between sites were not statistically significant ($p=0.05$). The sites and species sampled by the NS&T Program have apparently not been sampled by other investigators.

In 1985 and 1986, the California Mussel Watch Program (Hayes et al., 1987) analyzed silver in coastal mussels (*M. californianus*) transplanted to 8 and 10 sites, respectively, in San Francisco Bay and in resident mussels from Bodega Head (Figure 67). Highest concentrations of silver were found in mussels transplanted to Redwood Creek (0.96 ppm), Treasure Island (0.86 ppm), the Dumbarton Bridge (0.75 ppm), the San Mateo Bridge (0.65 ppm), and to a site in the Oakland Inner Harbor (0.63 ppm). Mussels transplanted to peripheral areas had silver levels higher than those transplanted to basin sites. Mussels transplanted to sites in the south and central bays had silver levels higher than those transplanted to San Pablo Bay sites.

In 1986, the NOAA NS&T Program (Boehm et al., 1987) analyzed silver in *Mytilus edulis* from the San Mateo Bridge, Dumbarton Bridge, and Tomales Bay and *M. californianus* from Bodega Head (Figure 67). Concentrations of silver in mussels were highest at the Dumbarton Bridge (0.49 ppm) and lowest from Tomales Bay (0.04 ppm). All the samples analyzed by the NS&T Program were below the Bay-wide grand mean for silver in mussels (Figure 64). Silver levels in mussels from Dumbarton Bridge and San Mateo Bridge were not significantly different from each other. Silver levels in mussels from Tomales Bay and Bodega Head were different from each other and from the two sites in San Francisco Bay ($p=0.05$). Results generated by the NS&T Program are generally lower than the mean concentrations of silver detected in mussels sampled near NS&T Program sites by other investigators. At the San Mateo Bridge, the mean concentration of silver detected by Risebrough et al. (1978), Hayes et al. (1985), and Hayes and Phillips (1986, 1987) between 1976 and 1985 was 0.75 ppm, compared to 0.37 ppm detected by the NS&T Program. At the Dumbarton Bridge, the mean level detected by Risebrough et al. (1978), Hayes et al. (1985), and Hayes and Phillips (1986, 1987) was 0.90, compared to 0.49 ppm detected by the NS&T Program. At Bodega Head, the mean level of silver detected by Farrington et al. (1982), Hayes et al. (1985), and Hayes and Phillips (1986, 1987) between 1976 and 1986 was 0.14 ppm, compared to 0.11 ppm detected by the NS&T Program. In Tomales Bay, the mean level of silver detected by Hayes et al. (1985), Hayes and Phillips (1986, 1987), Anderlini et al. (1975 a, b), and Wyland (1975) between 1973 and 1985 was 0.42 ppm, compared to 0.04 ppm detected by the NS&T Program.

(2) Temporal Trends

Resident mussels (*Mytilus edulis, M. californianus*) have been resampled at three sites in the Bay and Bodega Head (Girvin et al., 1975; Hayes et al., 1985; Boehm et al., 1987). Sampling at Foster City or nearby on the San Mateo Bridge in 1975, 1982, and 1986 has shown no decline in silver levels from <1.5 ppm in 1975 to 0.4 ppm in 1982 and 1986. Repeated sampling at Redwood Creek (and at two sites nearby) has also shown no change in silver levels from <1.5 ppm in 1975 to 0.1 ppm in 1980, and 0.97 ppm in 1982. Samples from the Dumbarton Bridge in 1980, 1982, and 1986 have had 0.3 to 0.5 ppm silver. Levels of silver in mussels from Bogega Head (0.02 to 0.7 ppm) have not been significantly different between years since 1977 ($p=0.05$).

Transplanted mussels (*Mytilus californianus*) have been resampled at eight sites in San Francisco Bay since 1979 (Figure 68) (Hayes et al., 1985; Hayes and Phillips, 1986, 1987). The four southern sites show declines in silver levels between 1980 and 1986, from over 1 ppm to less than 0.6 ppm. The four northern sites show no trend in silver levels during the same time period. The very high concentrations of silver in transplanted *M. californianus* at sites in Redwood Creek in 1982 were followed by lower levels in 1983.

C. Summary

Like the other trace metal concentrations, silver concentrations in the sediments of San Francisco Bay and its environs display a small-scale patchiness and a large-scale homogeneity. This pattern is illustrated in Figure 61, where silver concentrations for individual samples ranged from less than 0.01 to 16 ppm (a difference of 1,600 times), but mean concentrations for each study ranged from 0.15 to 3.38 ppm (a difference of 23 times). The mean concentrations for the studies exceeded 3 ppm in only one instance: at an Islais Creek site sampled in 1985 by the NS&T Program Sediment Quality Triad study.

Table 24 gives the overall means for the basins (0.51 ppm) and the peripheral areas (1.63 ppm) based on all the data compiled for this report. When the first nine sampling periods of the SBDA study were excluded (due to questionable results), the means become 0.56 and 1.79 ppm, respectively. In either case, the basins and peripheral areas were found to be significantly different (p=0.01). The tendency for the peripheral areas to have higher concentrations of silver is further supported by the fact that of the 54 samples with silver concentrations in excess of 2.0 ppm, only two came from basin areas (2.4 ppm at the Triad study site off Oakland, and 2.1 ppm at the SBDA south Bay site below Dumbarton Bridge).

The means, standard deviations, medians, and ranges of silver concentrations in sediments in the four basins and selected peripheral areas based on data from all the studies compiled for this report are listed in Table 26. It also includes the number of samples taken at each area and the years in which sampling took place. While the table orders the areas from highest to lowest mean, any comparisons of areas must be done with extreme caution because of differences in sampling and analytical methodologies, time of sampling, and number of samples taken at each area. Possibly the most significant statistic in Table 26 is the ranges that show a high degree of overlap for *all* the areas sampled, both basins and peripheral areas. The grand mean for the Bay (1.13 ppm, Table 24) exceeded the mean concentrations for the two reference sites, Bodega Bay (0.92 ppm) and Tomales Bay (0.14 ppm), by factors of 1.2 and 8.1, respectively. Sites in which silver concentrations have been high have included China Basin, Islais Creek, Mare Island Strait, Hunters Point, and Oakland Outer Harbor.

Because of the sporadic sampling for silver contamination, no temporal patterns of silver distribution can be determined for sediments.

Silver concentrations in some samples of mussels have been very high in parts of south Bay, especially in and near Redwood Creek. The basin means and medians for central and south bays have been similar and a little over double those of San Pablo Bay, possibly indicative of a south to north trend of decreasing concentrations. The basin means and medians have been similar to the grand mean for the Bay. One sample of mussels from Redwood Creek, however, exceeded the grand mean by a factor of 23. The grand mean for mussels in the Bay exceeded the overall means for Tomales Bay and Bodega Head by factors of 7 and 5, respectively.

The concentrations of silver in clams have been relatively high in sites near San Mateo and Redwood Creek and a site near Berkeley. Clams from San Pablo Bay have generally had among the lowest silver concentrations. The one year of sampling fish in the Bay by the NS&T Program also showed relatively low silver concentrations in San Pablo Bay fish.

Some data for biota suggest that silver concentrations have decreased in parts of south Bay and remained relatively constant in San Pablo Bay and central Bay since the late 1970s and early 1980s. Other data suggest that no changes in concentrations have occurred in south Bay. However, the data record is thus far relatively short and available for only a small number of sites.

Historical mean concentrations of silver in sediments sampled from 1973 through 1987 in San Francisco Bay are compared in Figure 69 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper-case print. The NS&T Program sites are in lower-case print. Those from the 1984 Benthic Surveillance Project are designated by "BS" after the site name; those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold, lower-case print. The mean overall concentration of 1.13 ppm for the Bay ranked relatively high compared to the NS&T Program sites sampled in 1984 and 1986. The means for China Basin and all peripheral sites also ranked high. However, the means for the basins were low as were those for the NS&T Program sites in the Bay. These data reflect a pattern in which relatively high silver concentrations are found mainly in peripheral areas of the Bay. The two reference sites, Bodega Bay and Tomales Bay, ranked 6th and 31st, respectively.

The historical mean concentrations of silver in mussels collected in San Francisco Bay from 1971 through 1986 are compared in Figure 70 with means from three samples of mussels each from NS&T Program Pacific Coast sites sampled in 1986. The historical areas are listed in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located in the Bay are listed in bold print. The historical mean concentrations of silver in mussels has been distinctly lower in San Pablo Bay than elsewhere in the Bay. The mean concentrations in the central and south bays have often been very high compared to the 1986 Pacific Coast values, particularly in Redwood Creek, a peripheral area. In this area, the concentration of silver has exceeded those in Pacific Coast sites by an order of magnitude of two. However, among the 1986 NS&T Program sites, the two in the Bay ranked relatively low, 17th and 18th. The two reference sites, Tomales Bay and Bodega Head, ranked 43rd and 32nd, respectively.

Table 24. Bay-wide means, standard deviations, medians, and ranges of silver concentrations in surficial sediments of San Francisco Bay based on data collected by many investigators from 1971 through 1987 from the four basins and peripheral harbors and waterways (ppm dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	1.13	1.52	0.58	<0.01 - 16	336
BASINS	0.51	0.51	0.38	<0.01 - 2.4	148
PERIPHERY	1.63	1.83	1.2	<0.1 - 16	188

Table 25. Means, medians, and ranges in concentration of silver in mussels (Mytilus edulis or Mytilus californianus) collected by many investigators from basins and peripheral areas of San Francisco Bay, 1971-86 (ppm, dw).

AREA/SITE	MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY					
BASIN	0.50	-	-	-	1
SAN PABLO BAY					
BASIN	0.37	0.23	0.40	0.02-1.1	33
PERIPHERAL-MARE ISLAND STRAIT	0.41	0.13	<1	0.08-<1	24
CENTRAL BAY					
BASIN	1.00	1.05	0.90	0.03-1.9	103
PERIPHERAL-RICHMOND HARBOR	0.29	0.24	0.22	0.1-0.61	4
PT. ISABEL	0.03	0.00	-	0.03-0.03	2
BERKELEY MARINA	0.06	0.04	<0.1	<0.1-0.2	12
ALL PERIPHERAL	0.11	0.15	<0.1	0.03-0.61	18
SOUTH BAY					
BASIN	0.95	0.57	0.80	0.08-3.0	86
PERIPHERAL-ISLAIS CREEK	<1.5	-	-	-	1
NEWARK SLOUGH	0.47	-	-		1
ALAMEDA YACHT HARBOR	0.11	0.04	-	0.08-0.13	2
OAKLAND INNER HARBOR	0.46	0.37	0.42	0.11-0.9	4
OAKLAND OUTER HARBOR	0.40	-	-	-	1
BAYSHORE LAGOON	0.06	-	-	-	1
PALO ALTO YACHT HARBOR	1.61	1.24	1.87	0.27-2.7	3
REDWOOD CREEK	2.61	5.43	0.77	0.09-22.5	32
BELMONT SLOUGH	0.90	-	-	-	1
ALVISO SLOUGH	0.37	-	-	-	1
ALL PERIPHERY	2.02	4.62	0.75	0.06-22.5	46
ALL SAN FRANCISCO BAY	0.97	1.94	0.64	0.02-22.5	317
TOMALES BAY	0.20	0.27	<0.1	0.03-1.3	37
BODEGA HEAD	0.14	0.11	0.11	0.02-0.7	53

Table 26. Means, standard deviations, medians, and ranges of silver concentrations in surficial sediments of San Francisco Bay for the four basins and selected peripheral areas based on data collected by many investigators from 1971 through 1987, ordered from highest to lowest by mean (ppm dw).

AREA	YEARS SAMPLED	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
CHINA BASIN	79	6.90	7.26	5.35	0.90 - 16.00	4
ISLAIS CREEK	79, 85	4.69	3.80	4.00	0.35 - 9.00	7
MARE ISLAND STRAIT	73, 74	2.12	0.91	2.15	0.50 - 4.90	82
HUNTERS POINT NS	86, 87	1.58	0.79	2.00	0.40 - 2.50	9
OAKLAND OUTER HARBOR	80, 81	1.10	1.00	0.50	0.50 - 4.00	15
CENTRAL BAY	80,81,84-86	0.72	0.58	0.50	0.13 - 2.00	35
COYOTE CREEK	82-86	0.61	0.58	0.65	<0.1 - 1.90	20
SAN LEANDRO BAY	80, 81	0.61	0.41	0.50	0.40 - 2.00	15
GUADALUPE SLOUGH	82-86	0.59	0.61	0.58	<0.1 - 2.10	20
SOUTH BAY	79,80,82-86	0.57	0.52	0.50	<0.-01 - 2.40	69
BERKELEY MARINA	80, 81	0.49	0.03	0.50	0.40 - 0.50	15
SAN PABLO BAY	84-86	0.45	0.44	0.27	<0.01 - 1.60	15
SUISUN BAY	83	0.15	0.09	0.14	0.03 - 0.39	29
BODEGA BAY	84-85	0.92	1.31	0.1225	<0.01 - 2.66	6
TOMALES BAY	86	0.14	0.02	0.14	0.12 - 0.16	3

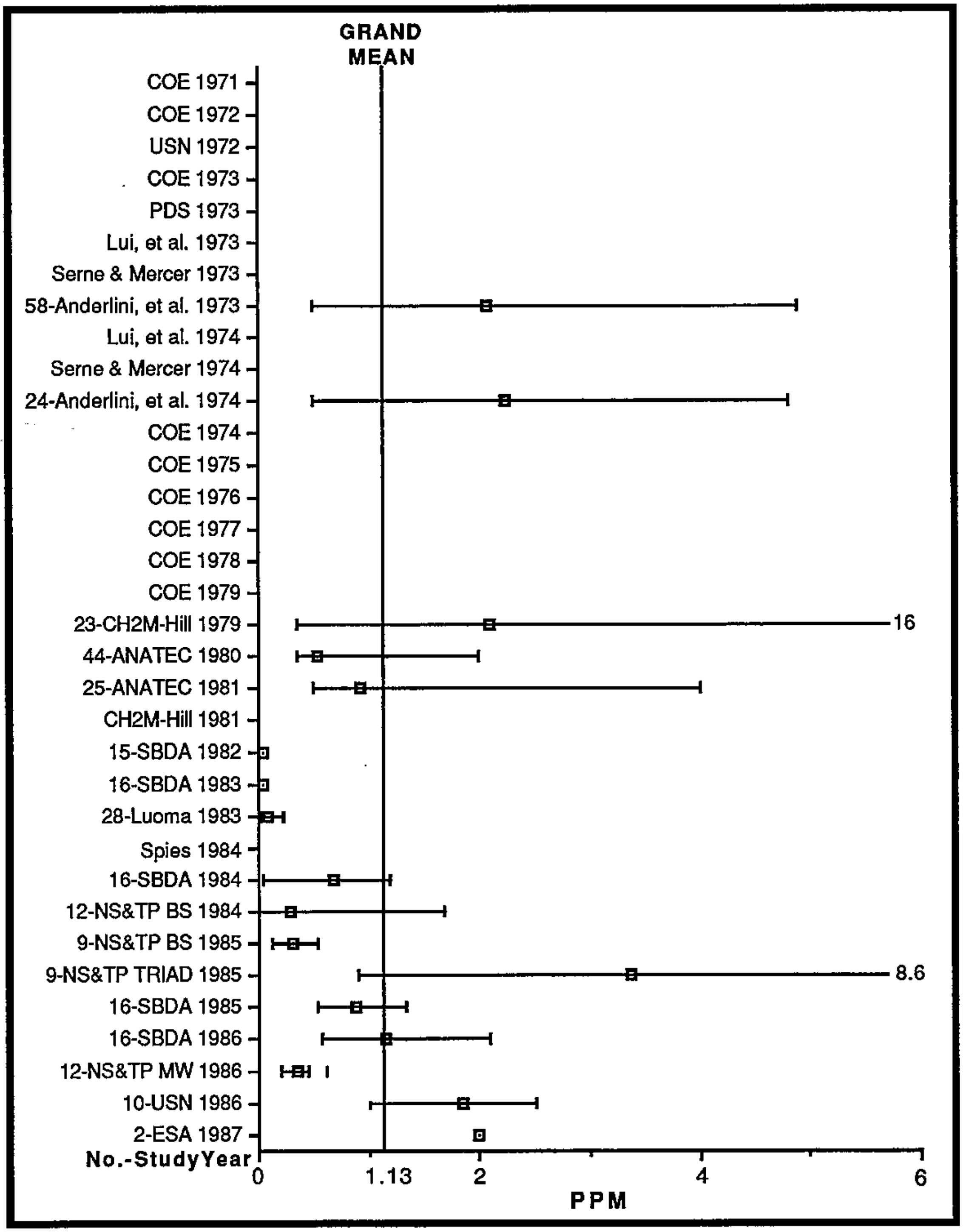


Figure 61. Mean concentration of silver in the surficial sediments of San Francisco Bay by study and year compared to the grand mean for the Bay (ppm dw) (No.=number of samples, bars represent the range).

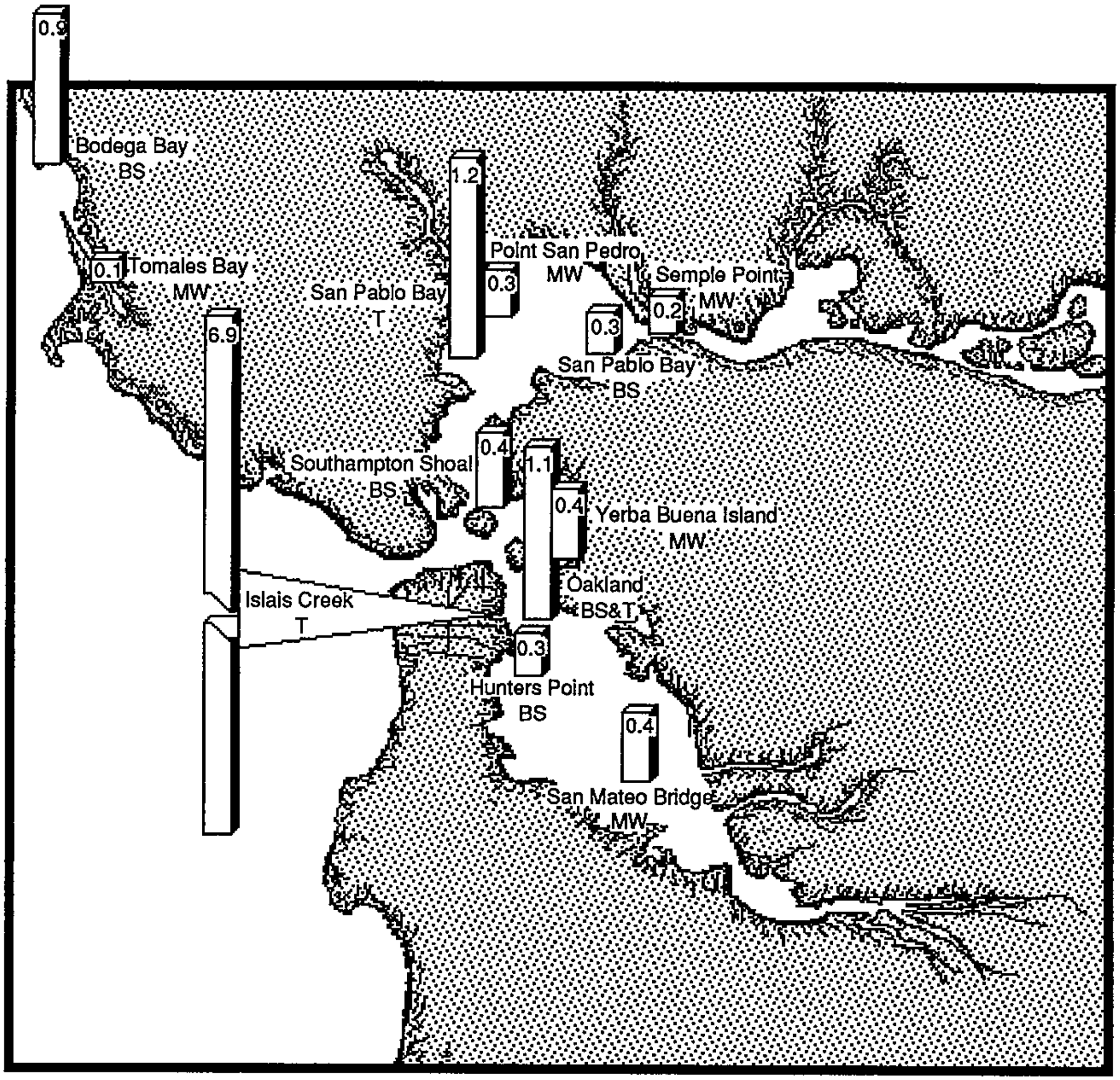


Figure 62. Mean silver concentrations in the surficial sediments for 1984-86, in ppm dw, based on NOAA NS&T Program data (BS=Benthic Surveillance, MW=Mussel Watch and T=Sediment Quality Triad study) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986) .

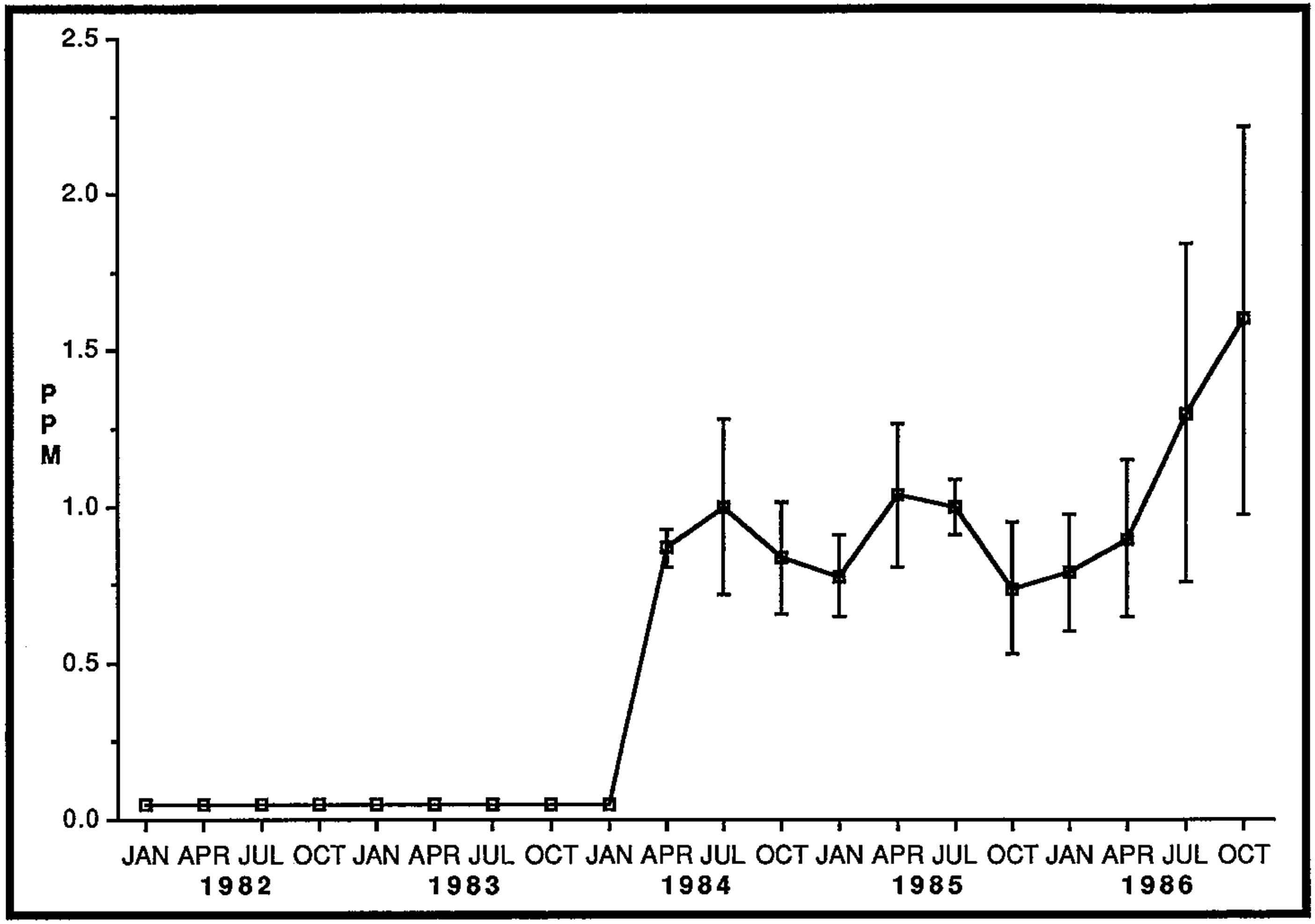


Figure 63. Monthly mean silver concentration in the surficial sediments at the four sites in the southern end of the south Bay sampled by the SBDA from 1982 through 1986 (bars represent one standard deviation) (Stevenson et al., 1987).

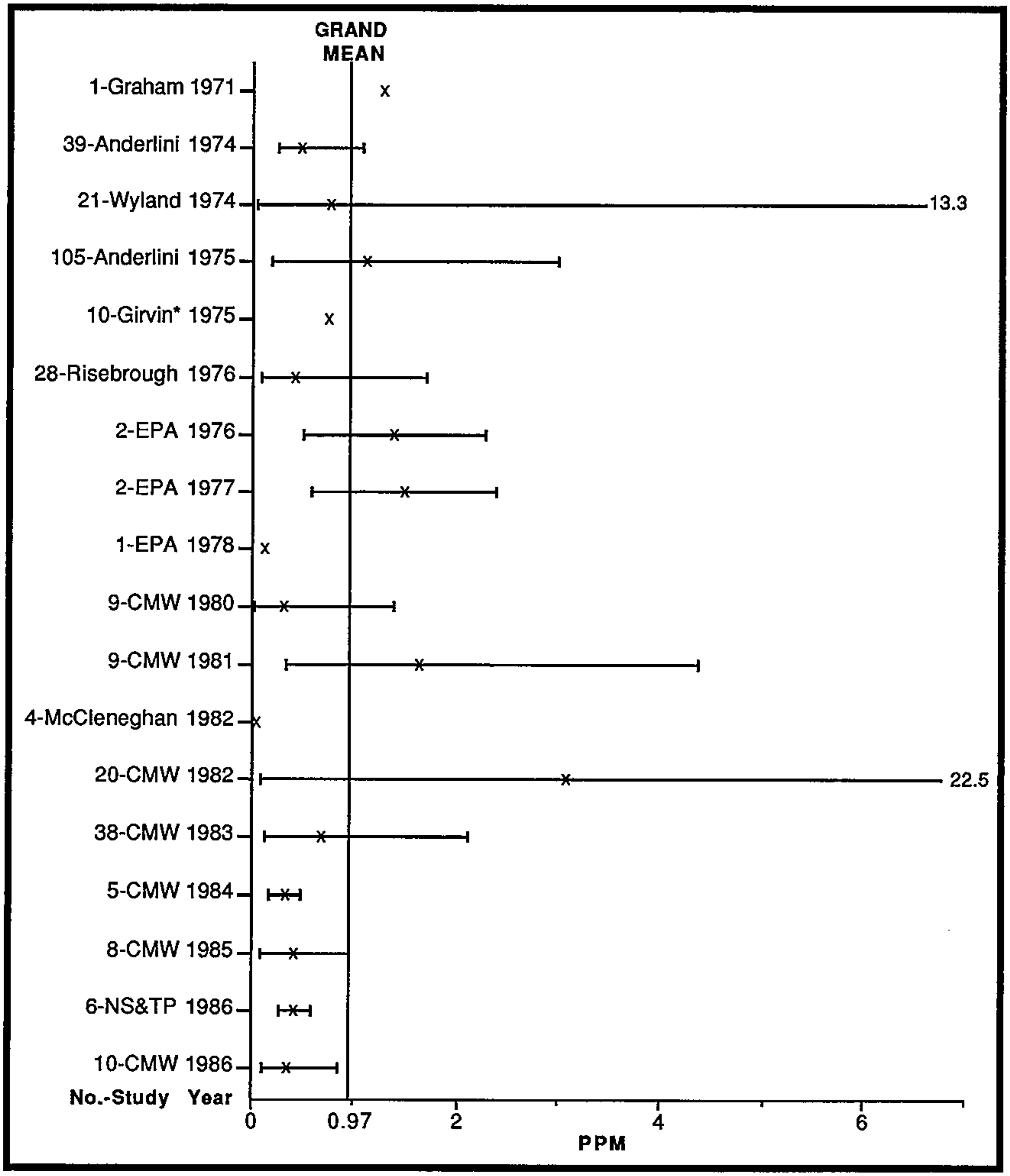


Figure 64. Mean concentration of silver in mussels (Mytilus edulis or M. californianus) by study and year in ppm dw (No.=number of samples, bars represent the range).

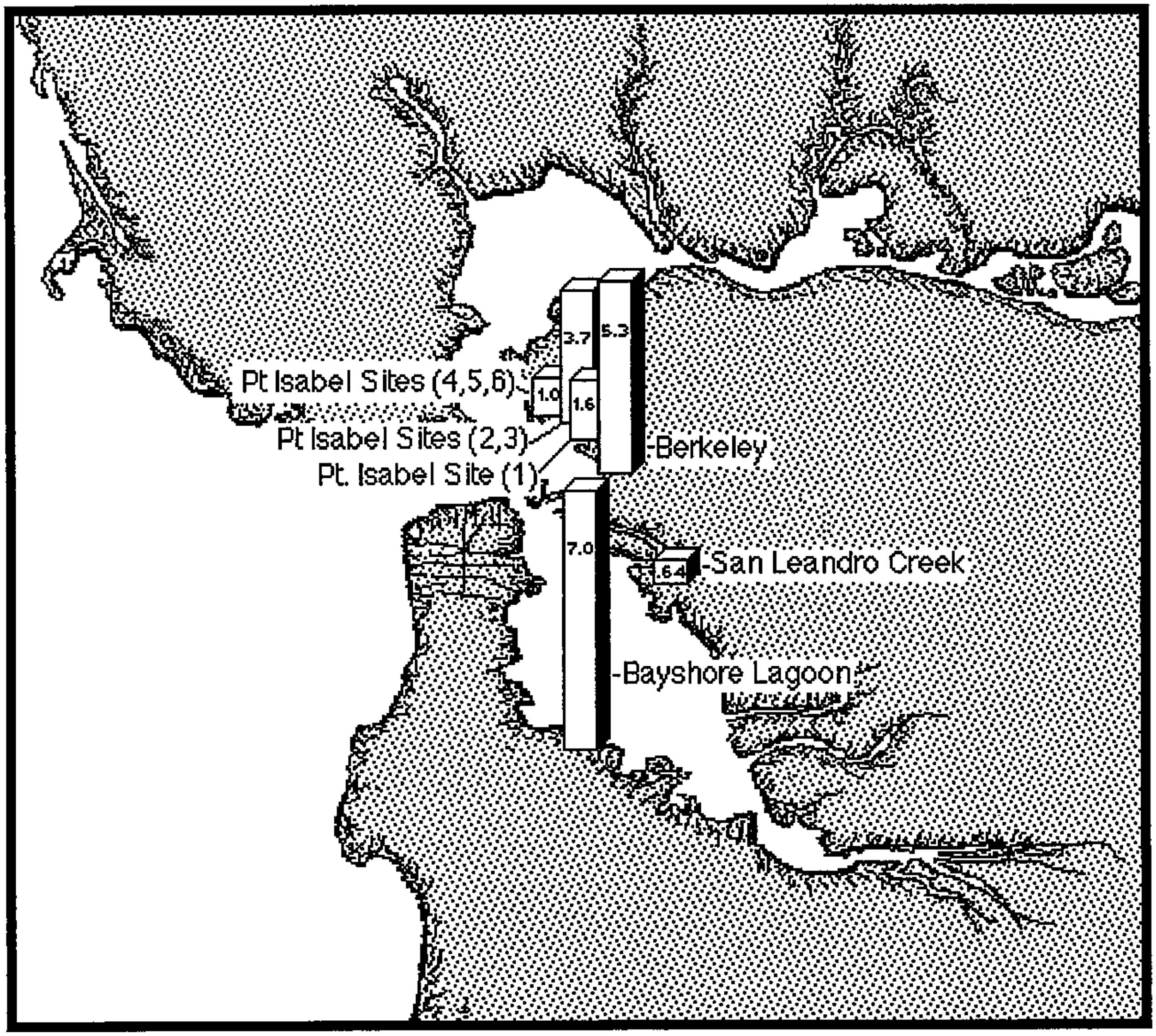


Figure 65. Silver concentrations in Japanese littleneck clams (Tapes japonica) in 1980 (ppm dw) (McCleneghan et al., 1982; Kinney and Smith 1982).

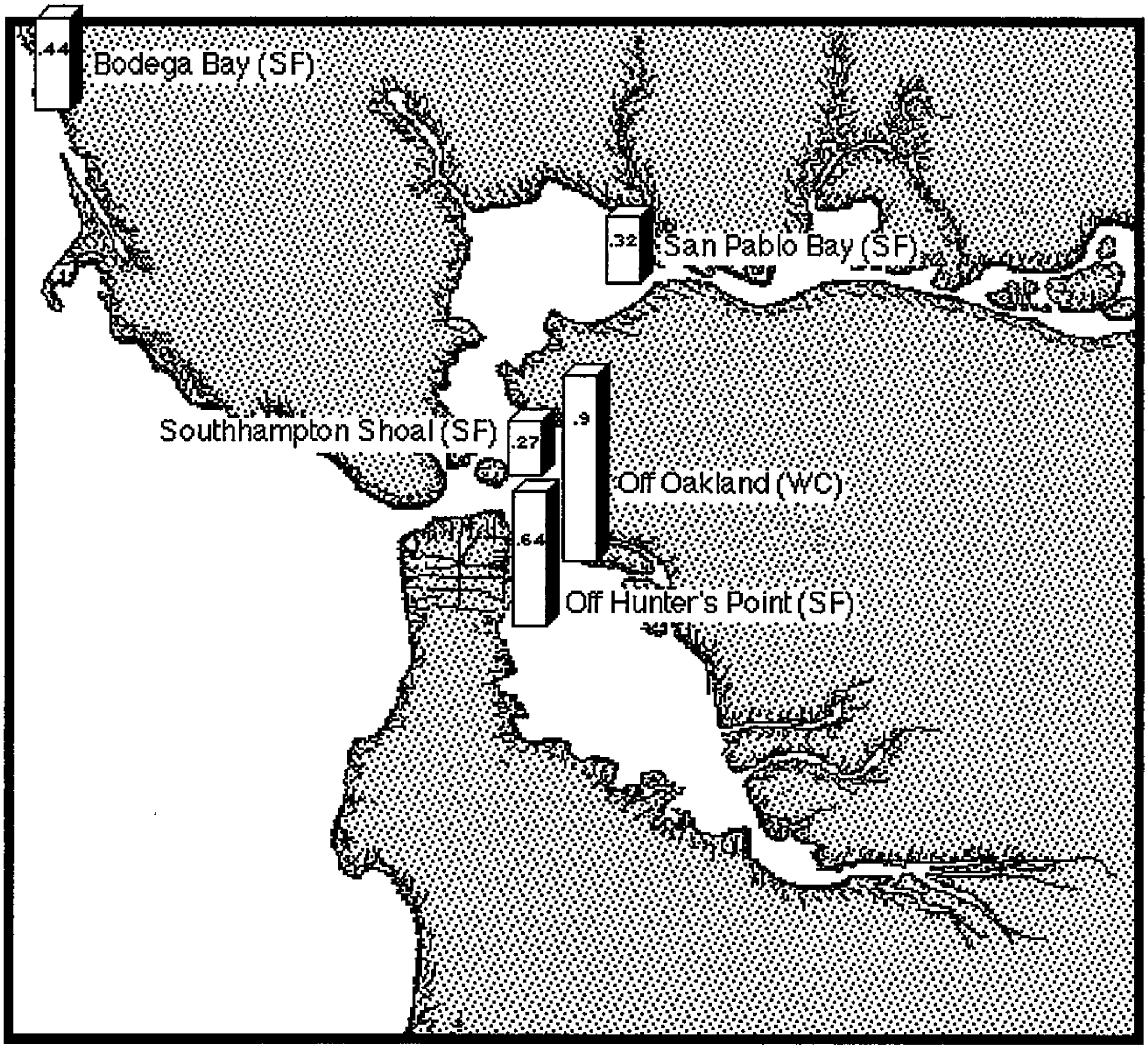


Figure 66. Silver concentrations in liver tissue of starry flounder (SF), Platichthys stellatus, and white croaker (WC), Genyonemus lineatus in 1984 (ppm dw) (NOAA, 1987a).

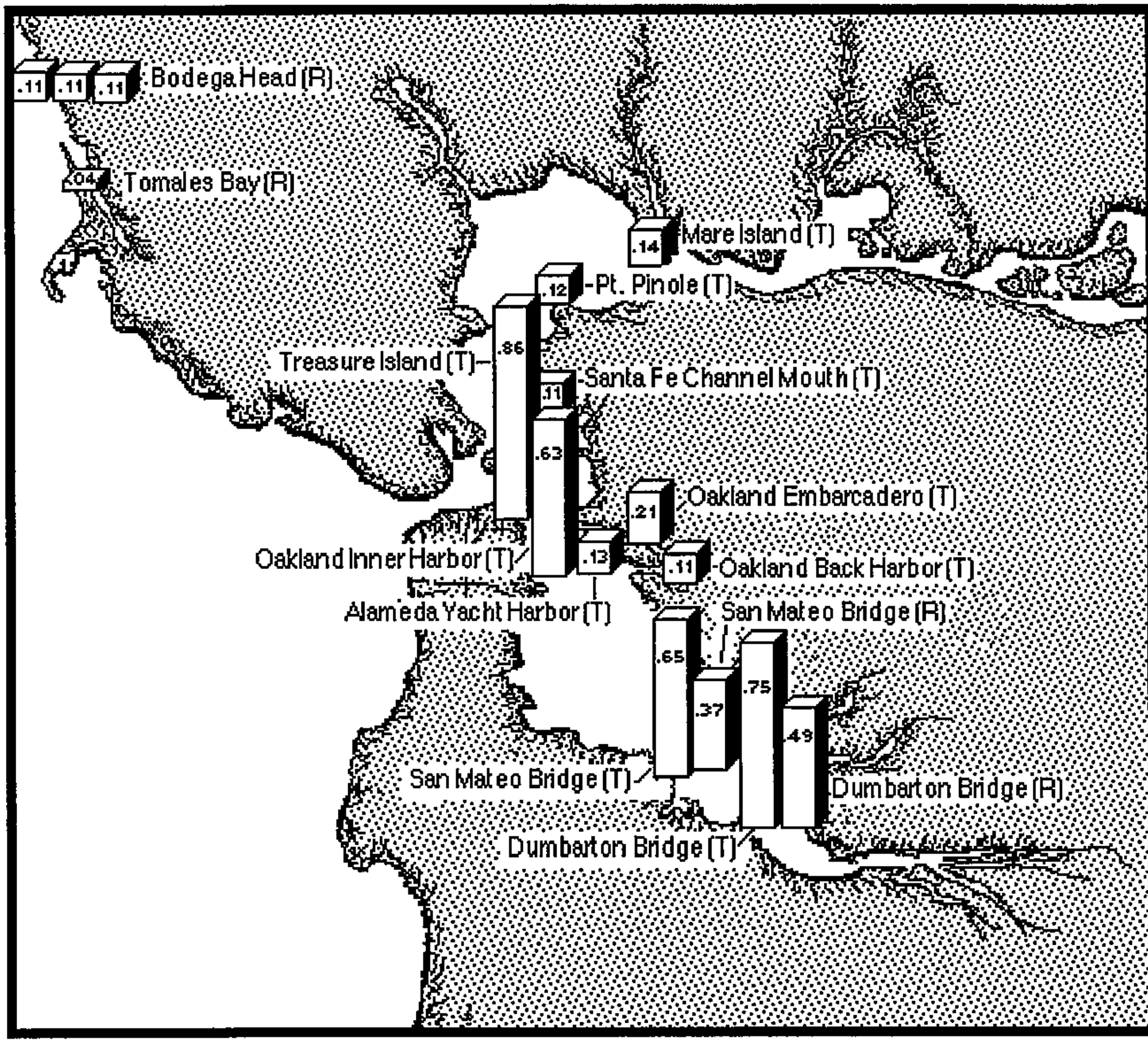


Figure 67. Silver concentrations in transplanted (T) coastal mussels (M. californianus) and resident (R) bay mussels (M. edulis) sampled in 1985-86 by CMW and NS&T Program (Hayes and Phillips, 1987; Boehm et al., 1987).

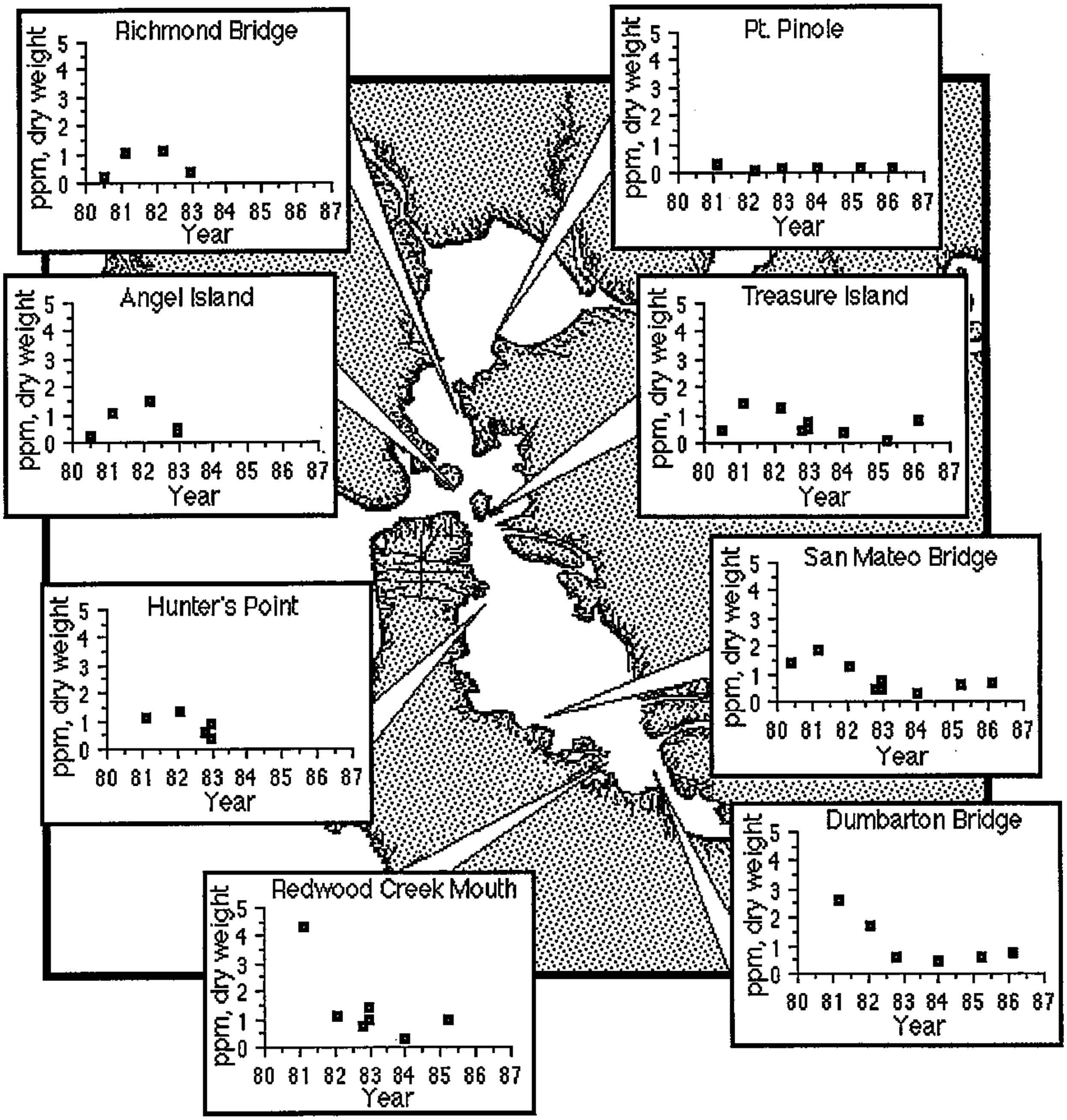


Figure 68. Temporal trends in silver concentrations in transplanted mussels (M. californianus) 1980-86 (Hayes et al., 1985; Hayes and Phillips, 1986, 1987).

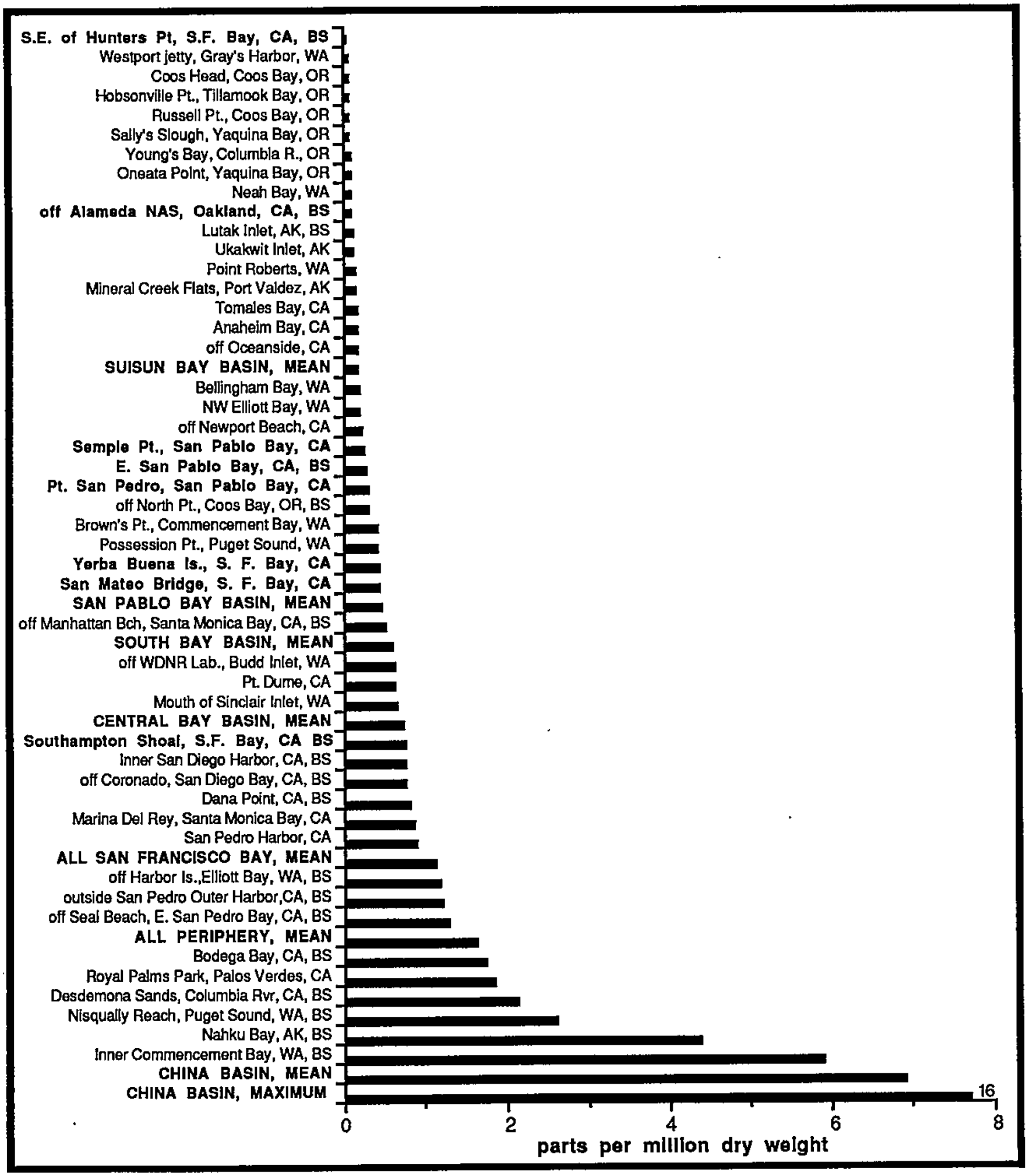


Figure 69. Comparison of silver concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Tables 24,26), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name) .

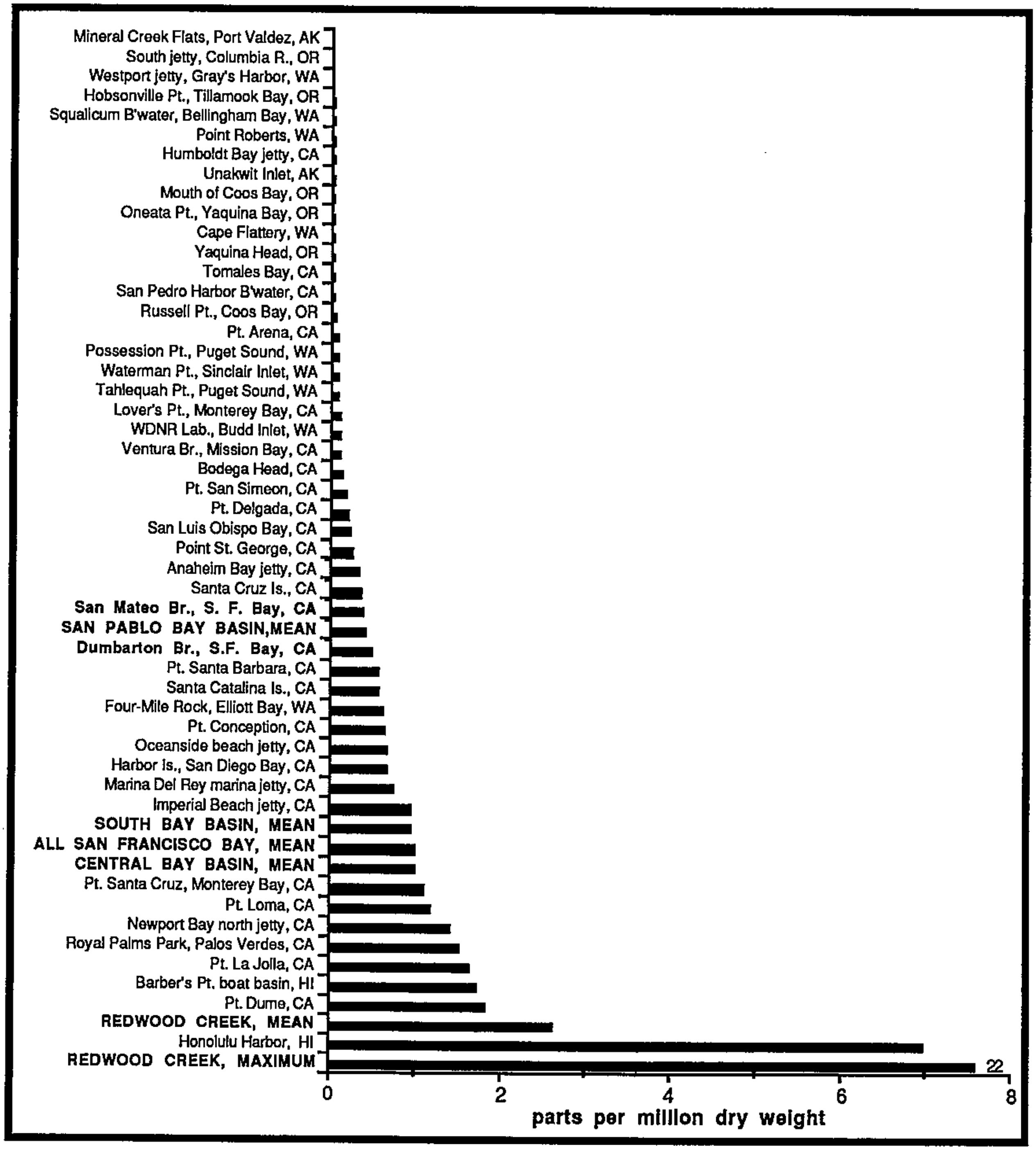


Figure 70. Mean silver concentrations in resident mussels (Mytilus edulis, M. californianus) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1972-1986) data for San Francisco Bay (from Table 25). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

9

GEOGRAPHIC AND TEMPORAL TRENDS IN PAH CONTAMINATION

A. Sediments

Prior to 1983, no analyses had been performed to determine concentrations of individual polynuclear aromatic hydrocarbons (PAHs) in sediments of San Francisco Bay. Many surveys--both prior to 1983 and since then--have measured "oil and grease," an estimate of the total material extracted with an organic solvent, or "percent hydrocarbons." These data have been developed with varying methods and are not specific for individual aromatic hydrocarbons. They have been excluded from this chapter. In addition, data from the Castro Cove area have been excluded, since they mainly were for organic compounds (e.g., phthalates, phenols) not reported in the majority of the other data sets for the Bay. The major sources of PAH contamination data for 1983 to present, are NOAA's NS&T Program (Boehm et al., 1987; Chapman et al., 1986; NOAA, 1987a, b) and research conducted by Spies and his associates at the Lawrence Livermore National Laboratory and supported mainly by NOAA (Spies et al.,1985 a, b; and Spies, personal communication, 1987). An additional source of 1986 data is the U. S. EPA (Baumgartner et al., unpublished manuscript). All three groups have quantified some of the same hydrocarbons. However, comparison of data from these investigations is hindered since the three groups have also analyzed some different individual PAHs and different numbers of PAHs. Table 27 lists all the PAHs quantified and indicates which were measured by which group. The 18 PAHs in boldface type are common to the three NOAA NS&T Program projects; the seven asterisked compounds are common to all three groups. Analyses have been performed on 101 samples.

During the evaluation of the various data sets to determine trends, various combinations and numbers of individual PAHs were included iteratively in summations of total PAHs. Table 28 presents the means, standard deviations, medians, and ranges for the data sets used in this chapter, as well as for various combinations of these data sets. The number of individual PAHs summed to give a total PAH (tPAH) value is also listed in the table. The range column indicates that the highest value for tPAH was 132 ppm, based on 23 individual PAHs measured by Spies in 1986 at a site in Islais Creek Waterway (personal communication, 1987) . When this data set is combined with their earlier data set and only the 13 individual PAHs common to both are summed, the total value for the Islais Creek site becomes 111 ppm. When the 10 individual PAHs common to the NOAA and Spies data sets are summed, the Islais Creek value becomes 90.4 ppm. Finally, when the seven individual PAHs common to the NOAA, Spies, and EPA data are combined, the Islais Creek value is 80.9 ppm. The high standard deviations and wide ranges in concentrations reflect the spatial variability in the distribution of these hydrocarbons. The influence of sampling in peripheral harbors is apparent in the data from Spies; the means are the highest among the data sets. Based upon data for seven hydrocarbons quantified by all groups, the mean concentration for the Bay is 4.1 ppm. Based upon the NOAA data for 18 hydrocarbons measured in samples largely from the basins, the mean concentration for the Bay is 2.4 ppm (Table 28). The mean concentration of 13 hydrocarbons at 11 sites sampled by EPA in the south Bay basin is 3.2 ppm.

(1) Geographic Trends

The combined NOAA/Spies/EPA data set is arranged in Table 29 to compare concentrations in the basins and peripheral areas based on seven individual PAHs common to the three data sets. Based on these seven PAHs, tPAH values for peripheral areas are higher than those found in the basins by a factor of more than 7.5.

In 1984, the Benthic Surveillance Project (BS) of the NS&T Program (NOAA, 1987a) began analyzing samples of the upper 1 cm of sediment for PAH concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (Figure 71). Samples from the same sites, with the exception of the site off Oakland, were again analyzed in 1985. The overall mean tPAH concentration, for the 2-year period was 1.52 ppm with a standard deviation of 1.52 ppm and a range of 0.08 ppm to 4.35 ppm. The site means ranged from 0.21 ppm at the San Pablo Bay site to 3.44 ppm at the Hunters Point site. The single sample with the lowest tPAH concentration (0.08 ppm) was from the San Pablo Bay site in 1984, while the sample with the highest tPAH concentration (4.35 ppm) was from the Hunters Point site in 1985. In both 1984 and 1985 ,samples from a site in Bodega Bay, an area minimally influenced by anthropogenic activities, were also analyzed for PAH concentrations. The 2-year mean for the site was 0.08 ppm, with a range from 0.04 to 0.19 ppm. The San Pablo Bay (0.21 ppm) site was significantly different than the Oakland (1.76 ppm) and Hunters Point (3.44 ppm) sites (p=0.05). The Bodega Bay site (0.08 ppm) was significantly different than the Southampton Shoal (0.81 ppm), Oakland, and Hunters Point sites (p=0.05).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) study (Chapman et al., 1986) at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Figure 71). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean tPAH concentration in the sediments, based on three samples per site, was 4.91 ppm with a range of 0.33 to 15.43 ppm. The Islais Creek site (11.9 ppm) was significantly different than the San Pablo Bay (0.82 ppm) and Oakland sites (1.98 ppm) (p=0.05).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for PAH concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba Buena Island, and near the San Mateo Bridge. In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987) (Figure 71). The analyses were conducted on samples of the upper 1 cm of sediment. The overall mean tPAH concentration for the sites in the Bay, based on three samples per site, was 1.97 ppm with a range of 0.92 to 3.24 ppm. The individual site means ranged from 1.10 ppm at Semple Point to 2.84 ppm at San Mateo Bridge; the Tomales Bay mean was 0.47 ppm (Figure 71). The two San Pablo Bay sites, Semple Point and Point San Pedro (1.27 ppm), were significantly different than the central and south bay sites,Yerba Buena (2.65 ppm), and San Mateo Bridge (p=0.05). The Tomales Bay site was significantly different than all four sites in the Bay (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 2.38 ppm. However, if the Islais Creek data were excluded from the calculations, the mean would become 1.64 ppm. Four of the five Bay sites with the lowest mean tPAH concentrations were located in San Pablo Bay; the exception was the Southampton Shoal site. Statistical analysis indicated that the Benthic Surveillance San Pablo Bay site (0.21 ppm) was significantly different than the Point San Pedro (1.27 ppm), Oakland (1.87 ppm), Yerba Buena (2.65 ppm), San Mateo Bridge (2.84 ppm), Hunters Point (3.4 ppm) and Islais Creek (11.9 ppm) sites (p=0.05). The Bodega Bay site (0.09 ppm) was significantly different than all the Bay sites except for the Benthic Surveillance San Pablo Bay site (p=0.05), with the Bay basin sites ranging from 3 to 40 times higher than the Bodega Bay site. The sole peripheral site sampled, Islais Creek, had a mean tPAH concentration 130 times higher than Bodega Bay. Figure 71 displays the mean concentrations from NS&T Program data for the sites sampled in 1984 through 1986 based on 18 individual PAHs.

In 1986, Spies (personal communication, 1987) analyzed 29 samples from 10 areas for 24 individual PAHs. Based on the 18 individual PAHs common to the NS&T Program (BS, Triad, MW) projects, the overall mean tPAH concentration was 3.99 ppm. The relatively high mean could be due to the fact that most of their sampling locations were in peripheral areas such as Islais Creek and China and India basins. In Figure 72 , the data from NS&T Program projects and Spies et al. are combined based upon the sums of 18 individual PAHs. It shows that for 1984-86, the sites in the peripheral areas of the Bay had higher mean concentrations of PAHs in the sediments than the basin sites. The highest value was 132 ppm (based on one sample) for Islais Creek, with India Basin (three samples) at 35 ppm and China Basin (four samples) at 21 ppm, ranking second and third, respectively. The lowest means occurred at the Benthic Surveillance and Triad sites in San Pablo Bay and at Southhampton Shoal, all having means (based on three samples each) of less than 1.00 ppm.

Figure 73 shows all the sites sampled in San Francisco Bay by NOAA (BS, Triad, MW), Spies, and the EPA during 1985 and 1986, including the NOAA reference sites in Bodega and Tomales Bays, and their mean PAH concentrations based on the sums of seven hydrocarbons common to all three data sets. The mean PAH concentration values ranged from a low of 0.08 ppm, at the NOAA reference site in Bodega Bay, to 94 ppm at Spies' site in Islais Creek. As with Figures 71 and 72, Figure 73 shows that with this larger data set, the mean PAH concentrations in the surficial sediments of San Francisco Bay are noticeably higher than those at the Bodega Bay reference site and that the peripheral sites are noticeably more contaminated than the basin sites.

(2) Temporal Trends

There is no data base available to determine long-term temporal trends in PAH contamination of sediments in the Bay. The data generated by the NS&T Program will provide a basis for assessing trends in future years. These data are being generated using consistent methods and a rigorous quality control and quality assurance program. Although the following data were from more than one laboratory, all should be comparable since the same procedures were employed.

Figure 74 compares the mean tPAH concentrations, based upon 18 hydrocarbons in sediments at the four San Francisco Bay NOAA Benthic Surveillance Project sites and the Bodega Bay reference site for the years 1984 and 1985. It shows that while the means changed slightly between the two years at all sites, there were no significant differences between years at any of the sites ($p=0.05$).

When the yearly means for Bay-wide tPAH concentrations were calculated and analyzed for 1984 through 1986, based on NOAA NS&T Program data, there was no significant difference between years ($p=0.05$). The yearly means were: 1.53 ppm for 1984, 3.22 ppm for 1985, and 1.97 ppm for 1986. When Islais Creek data were excluded from the calculations, the mean for 1985 became 1.47 ppm.

B. Biota

PAH compounds are usually rapidly metabolized in fish to more water-soluble compounds and excreted quickly (Krahn et al., 1984). The metabolites are not readily identifiable by routine chemical analyses. As a consequence, very little data for PAHs are available for fish in the Bay.

PAH compounds have been analyzed in biota by five surveys since 1975. Fish and mussels from only 11 sites in San Francisco Bay have been analyzed for their PAH content. Considerable differences in analytical methods and in the number and selection of hydrocarbons reported have occurred during the few studies conducted in the Bay.

The same PAH compounds have not been measured by all surveys. Some surveys have only analyzed 8, others have measured 7 of these 8, plus up to 14 more compounds. Total PAHs in fish from San Francisco Bay have ranged from 0.017 ppm to 14 ppm ww. In mussels, they have ranged from .025 to 13 ppm. Highest levels of PAHs have been found in sites from the south Bay (Alameda, San Mateo Bridge) and from Treasure Island.

(1) Geographic Trends

Guard et al. (1983) surveyed PAHs in Dungeness crab (*Cancer magister*) and other species of crabs from sites in San Francisco Bay, Humboldt Bay, and several coastal California sites in 1975 and 1976. They reported concentrations of total saturated and unsaturated hydrocarbons in hepatopancreas and muscle tissue. The mean total hydrocarbon content (saturates and unsaturates) in juvenile *C. magister* hepatopancreas sampled in 1975 was 511 ppm $\pm$ 315 standard deviation in San Francisco Bay, compared to 305 ppm $\pm$ 35 standard deviation in Humboldt Bay near Eureka. In muscle, the means were 66 ppm $\pm$ 23 for San Francisco Bay and 18.9 ppm $\pm$ 0.2 for Humboldt Bay. The authors found the mean values for muscle were significantly different ($p \leq 0.05$), but those for hepatopancreas were not ($p>0.05$). Among adult crabs, they reported means for muscle tissue of 19 ppm $\pm$ 6 standard deviation for San Francisco Bay and 50 ppm $\pm$ 35 standard deviation for Humboldt Bay; the differences were not significant ($p \leq 0.05$). Also, among adults, the mean concentrations in hepatopancreas were 138 ppm with a range of ± 15 for San Francisco Bay and 41 ppm ± 16 standard deviation for Humboldt Bay; significantly different at $p < 0.01$. In 1976, total concentrations of alkanes and aromatics generally showed higher concentrations in San Francisco Bay crabs versus samples from coastal sites. A range of mean total concentrations from about 300 ppm to 3,000 ppm was observed in crab hepatopancreas from sites in San Francisco Bay: Red Rock Marina at Richmond (332 ppm), Oakland Harbor (312 ppm), Point Pinole (270 ppm), and Point San Pablo (3,000 ppm). Concentrations in crab hepatopancreas from Santa Cruz, Farallon Island, and San Pablo Bay ranged from <14 ppm to 250 ppm.

Mytilus edulis were taken from buoys, piers, or pilings at five sites in San Francisco Bay in 1978 and 1979 for PAH analyses (Risebrough et al., 1980). The highest level of the sum of eight PAH compounds was detected at the Treasure Island site (12.99 ppm). However, at this site, mussels were taken from wooden pilings, which may have been treated with creosote, a known source of PAHs. Mussels taken from cement pilings at Hunters Point and the Union Oil Pier in San Pablo Bay contained higher levels of PAHs (0.36 and 0.20 ppm) than those from two sites on metal buoys in south Bay (0.025 and 0.045 ppm).

McCleneghan et al. (1982) analyzed clams and mussels at sites sampled in 1980 for hydrocarbon content. They reported data from thin-layer chromatography only as total saturates, total unsaturates, and total hydrocarbons. In *Tapes japonica*, total hydrocarbon content ranged from 164 ppm at Bayshore Lagoon to 29 ppm at Coyote Point. Hydrocarbon content was highest (over 100 ppm) at Anza Lagoon, Burlingame Shore, and Bayshore Lagoon sites; and lowest (below 100 ppm) at Point Richmond, Point Isabel, Coyote Point, off San Mateo, and Foster City. Different patterns in hydrocarbon contamination were observed in *Mytilus edulis* and *Mya arenaria.*

The sampling of resident *Mytilus edulis* in 1986 by the NS&T Program at two sites in San Francisco Bay and a site in Tomales Bay, and *M. californianus* at Bodega Head showed highest levels (1.78 ppm) of the sum of 21 PAH compounds in mussels from the San Mateo Bridge (Figure 75). These PAHs may have originated from runoff from the bridge's surface above the sampling sites, or they may represent the concentrations that occur on a broader scale in south Bay. Lowest levels of PAHs were detected in mussels from Tomales Bay (0.23 ppm).

Spies et al. (1985b) sampled starry flounder (*Platichthys stellatus*) from four sites in San Francisco Bay in 1984 and determined concentrations of total hydrocarbons and their metabolites. Highest levels (14.0 ppm wet wt) of total PAHs and metabolites were detected in livers of fish from off the Alameda NAS (Figure 76). Lowest concentrations of PAHs (0.14 ppm) were detected in livers of starry flounder taken from western San Pablo Bay.

(2) Temporal Trends

Sites and species of biota sampled by the NS&T Program have not been sampled by any other surveys. However, mussels from south of the San Mateo Bridge (not far from an NS&T Program site) were sampled in 1978 by Risebrough et al. (1980). Concentrations of the seven PAH compounds which were analyzed by both surveys were higher in 1986 as measured by NS&T Program (0.48 ppm) than in 1978 as measured by the California Mussel Watch Program (0.04 ppm).

No other data are available to assess temporal trends in PAH contamination in the biota of the Bay.

C. Summary

Virtually no sampling was done prior to 1983 to determine the concentration of PAHs in the sediments of San Francisco Bay. Since that time, the major effort to determine levels of PAH contamination has been conducted under the auspices of the NOAA NS&T Program. Other sampling, sponsored in part by NOAA, was carried out by the Lawrence Livermore National Laboratory (e.g., Spies, personal communication, 1987) and the EPA. Each of the three groups quantified an overlapping, but different, list of PAHs.

Based on the pooled sediment data from NOAA, Spies, and the EPA, San Francisco Bay shows significantly higher concentrations of PAHs than the reference sites in Bodega Bay and Tomales Bay, and the peripheral areas are significantly more contaminated than the basins. Little can be said about temporal trends of PAH contamination in sediments because of the short time span over which sampling has occurred. Based upon the available data, no significant changes in PAH contamination have occurred during the 4-year period over which sampling has taken place.

The very small data base for PAHs in biota severely hinders any attempts to draw conclusions regarding geographic and temporal trends. From the few reliable data available, it appears that mussels at some sites in central and south Bay may be contaminated relative to mussels from reference sites. The data do not exist, however, to determine basin-wide means for the major components to the Bay. It also appears that fish collected off Oakland, off Berkeley and off Hunters Point are more contaminated than those caught in San Pablo Bay and Bodega Bay. Crabs collected at sites near Richmond and in Oakland Harbor have had relatively highly contaminated tissues. Essentially, no data exist with which to evaluate temporal trends among biota.

Historical mean concentrations of PAHs in sediments sampled from 1983 through1986 in San Francisco Bay are compared in Figure 77 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are listed in bold, upper-case print. The NS&T Program sites are in lower-case print. Those from the 1984 Benthic Surveillance Project are designated by "BS"; those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold, lower-case print. The grand mean concentration for the Bay (based primarily upon recent NS&T Program data) is relatively high compared to means for other sites along the Pacific Coast. Six of the top ten NS&T Program sites were in the Bay. Only the eastern San Pablo Bay site had relatively low concentrations, a pattern consistent with earlier observations. The two reference sites, Tomales Bay and Bodega Bay, ranked 17th and 28th, respectively.

The mean concentrations of PAHs in mussels collected in San Francisco Bay in 1978 and 1979 are compared in Figure 78 with means from three samples of mussels each from NS&T Program Pacific Coast sites sampled in 1986. The NS&T Program Mussel Watch sites are listed in lower-case print; the two located in the Bay in bold type. Only six data points were available from historical studies (1978-1979) in the Bay, precluding any rigorous comparison of NS&T Program and historical data. Among the 1986 NS&T Program sites, the two in the Bay ranked relatively low, 17th and 23rd. The two reference sites, Tomales Bay and Bodega Head, had very low PAH concentrations in 1986, ranking last and 25th, respectively.

Table 27. The PAHs analyzed for by the various research groups to determine a value for total PAH concentrations. The PAHs in boldface type are the ones which are common to all three NOAA NS&T Program projects (BS=Benthic Surveillance, Triad=Sediment Quality Triad, MW=Mussel Watch) (*Hydrocarbons quantified by all three groups) .

	NOAA NATIONAL STATUS AND TRENDS					
POLYNUCLEAR AROMATIC HYDROCARBON	**BS 1984-85**	**Triad 1985**	**MW 1986**	**SPIES et al. 1983-84**	**SPIES et al. 1986**	**EPA 1986**
Naphthalene	X	X	X		X	X
2-methylnaphthalene	X	X	X		X	
1-methylnaphthalene	X	X	X		X	
Biphenyl	X	X	X		X	
2,6-dimethylnaphthalene	X	X	X		X	
Acenapthene	X	X	X		X	X
Fluorene	X	X	X		X	X
Phenanthrene*	X	X	X	X	X	X
Anthracene*	X	X	X	X	X	X
1-methylphenanthrene	X	X	X	X	X	
Fluoranthene*	X	X	X	X	X	X
Pyrene*	X	X	X	X	X	X
Benz[a]anthracene*	X	X	X	X	X	X
Chrysene*	X	X	X	X	X	X
Benzo[e]pyrene	X	X	X	X	X	
Benzo[a]pyrene*	X	X	X	X	X	X
Perylene	X	X	X	X	X	
Dibenz[a,h]anthracene	X	X	X		X	X
9,10-dihydroanthracene		X		X		
2,3,5-trimethylnaphthalene						
Benzo[b&k]fluoranthene						X
Benzo[b]fluoranthene				X	X	
HMB					X	
Acenaphthylene					X	
Indo(1,2,3)Pyrene					X	
Benzo[k]fluoranthene				X	X	
Benzo[g,h,i]perylene				X	X	X
TOTAL NO. OF PAHs	18	19	18	14	24	13

Table 28. Means, standard deviations, medians, and ranges of total PAH concentrations in the surficial sediments of San Francisco Bay from 1983 through 1986 based on various combinations of data sets and individual PAHs (ppm dw).

DATA SET	MEAN	SD	MEDIAN	RANGE	NO. of PAHs	NO. of SAMPLES
NOAA 84-86	2.4	3.2	1.5	0.08 - 15.4	18	42
SPIES 86	16.3	28.6	7.4	1.23 - 132	23	29
SPIES 83-84	5.1	4.7	4.8	<0.46 - 21.9	14	19
SPIES TOTAL	10.3	19.0	5.3	<0.46 - 111	13	48
EPA 86 (SOUTH BAY ONLY)	3.2	3.9	2.0	1.5 - 14.7	13	11
NOAA AND SPIES COMBINED	5.7	12.6	2.8	0.13 - 90.4	10	78
NOAA, SPIES, EPA COMBINED	4.1	10.1	1.7	0.02 - 80.9	7	101

Table 29. Means, standard deviations, medians, and ranges for total PAH concentrations in the surficial sediments of San Francisco Bay basins and peripheral areas, based on the seven common individual PAHs measured by NOAA, Spies, and the EPA from 1983 through 1986 (ppm dw).

DATA SET	MEAN	SD	MEDIAN	RANGE	NO. of PAHs	NO. of SAMPLES
NOAA, SPIES, EPA COMBINED	4.1	10.1	1.7	0.02 - 80.9	7	101
NOAA, SPIES, EPA BASINS	1.6	1.4	1.4	0.02 - 8.53	7	77
NOAA, SPIES, EPA PERIPHERY	12.2	18.7	4.6	0.94 - 80.9	7	24

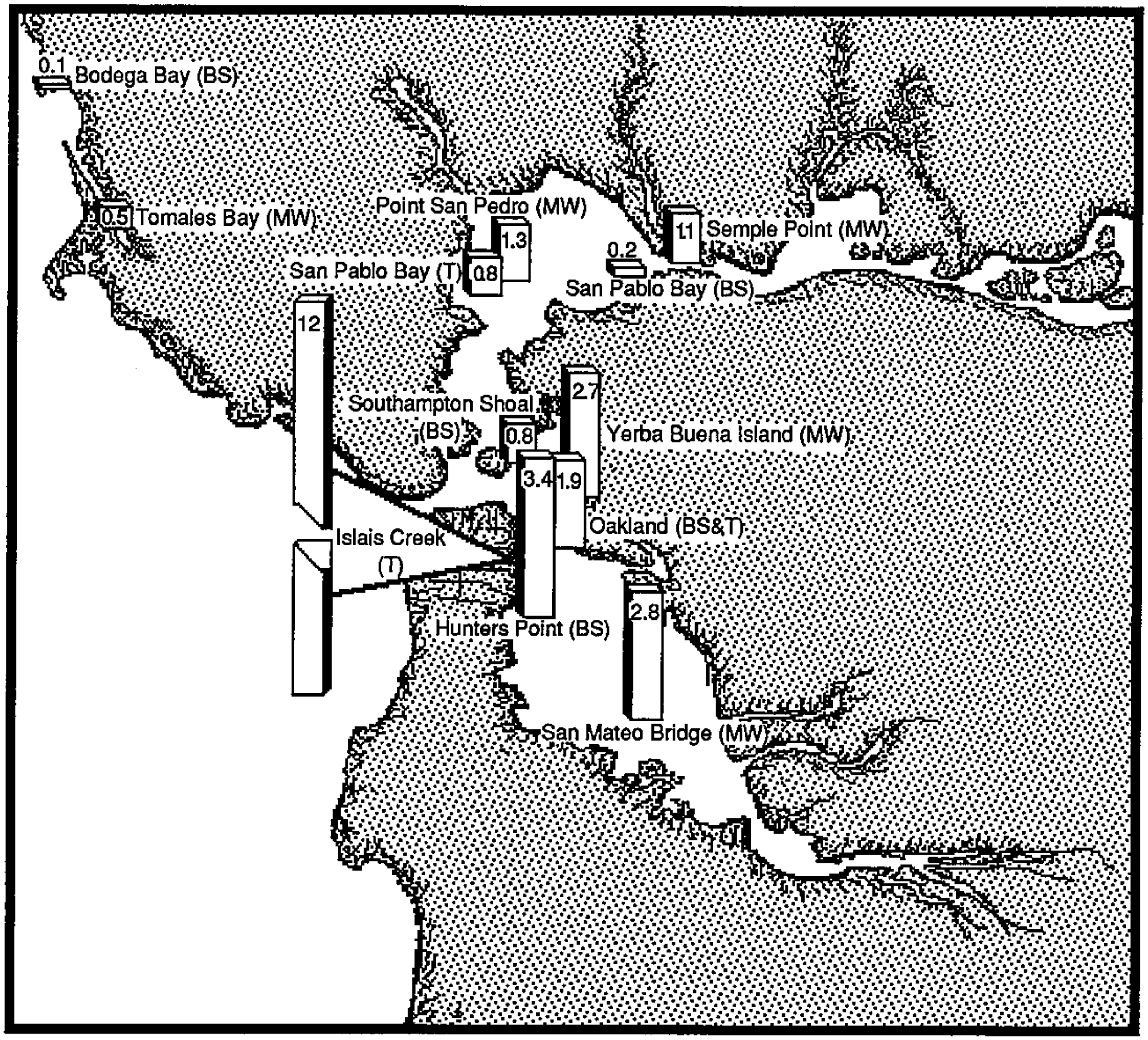


Figure 71. Mean tPAH concentration, in ppm dw, in the surficial sediments at the NOAA NS&T Program sites for 1984-86 based on data for 18 individual PAHs (BS=Benthic Surveillance, MW=Mussel Watch, T=Sediment Quality Triad) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986). NOTE: The concentration shown for the Oakland site is the mean of the values from the BS and Triad studies.

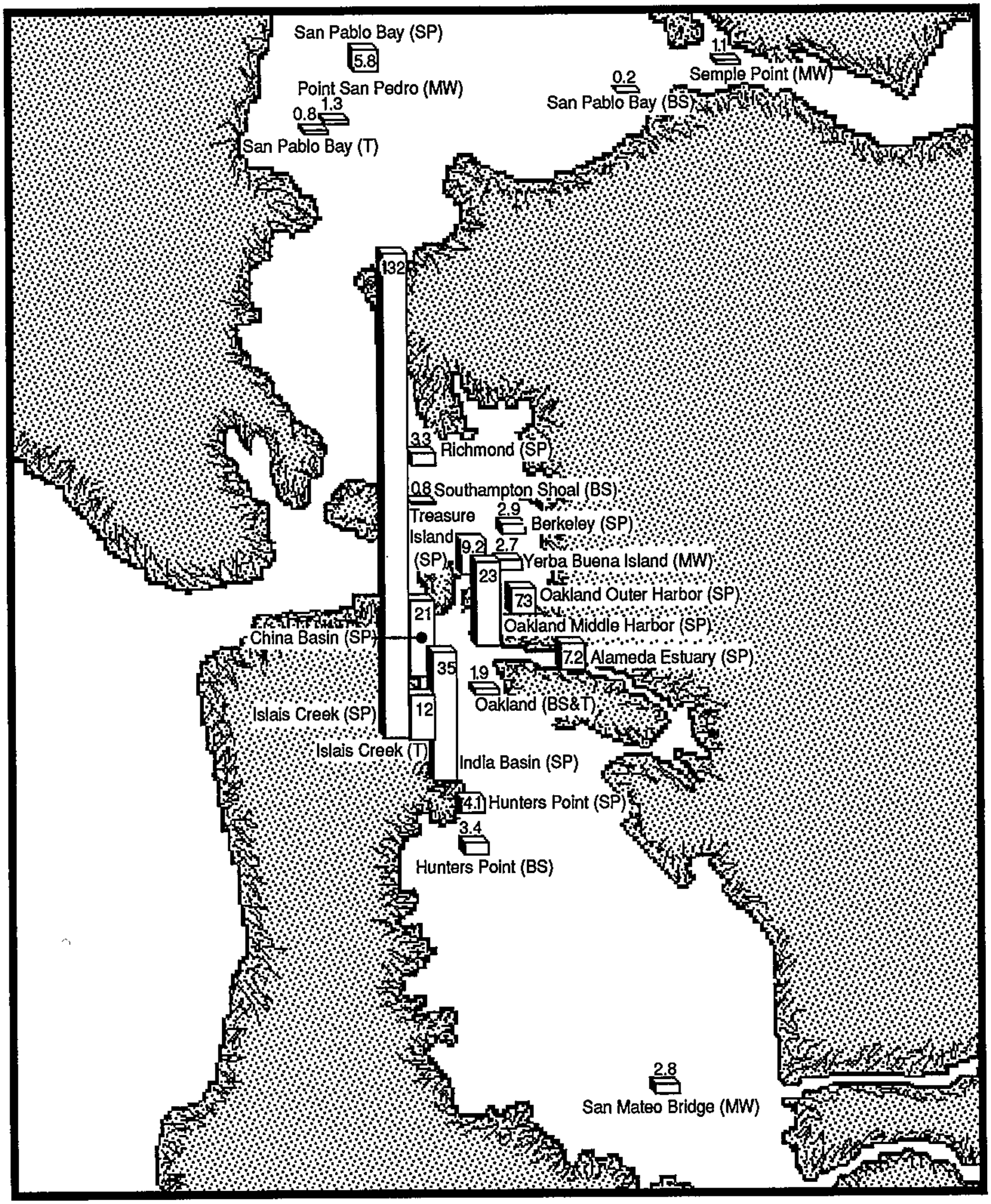


Figure 72. Mean tPAH concentrations, in ppm dw, in the surficial sediments of San Francisco Bay for 1984-86 based on the data for 18 individual PAHs (BS=Benthic Surveillance 1984-85, MW=Mussel Watch 1986, T=Sediment Quality Triad 1985, SP=Spies et al., 1986) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986; Spies., 1987, personal communication).

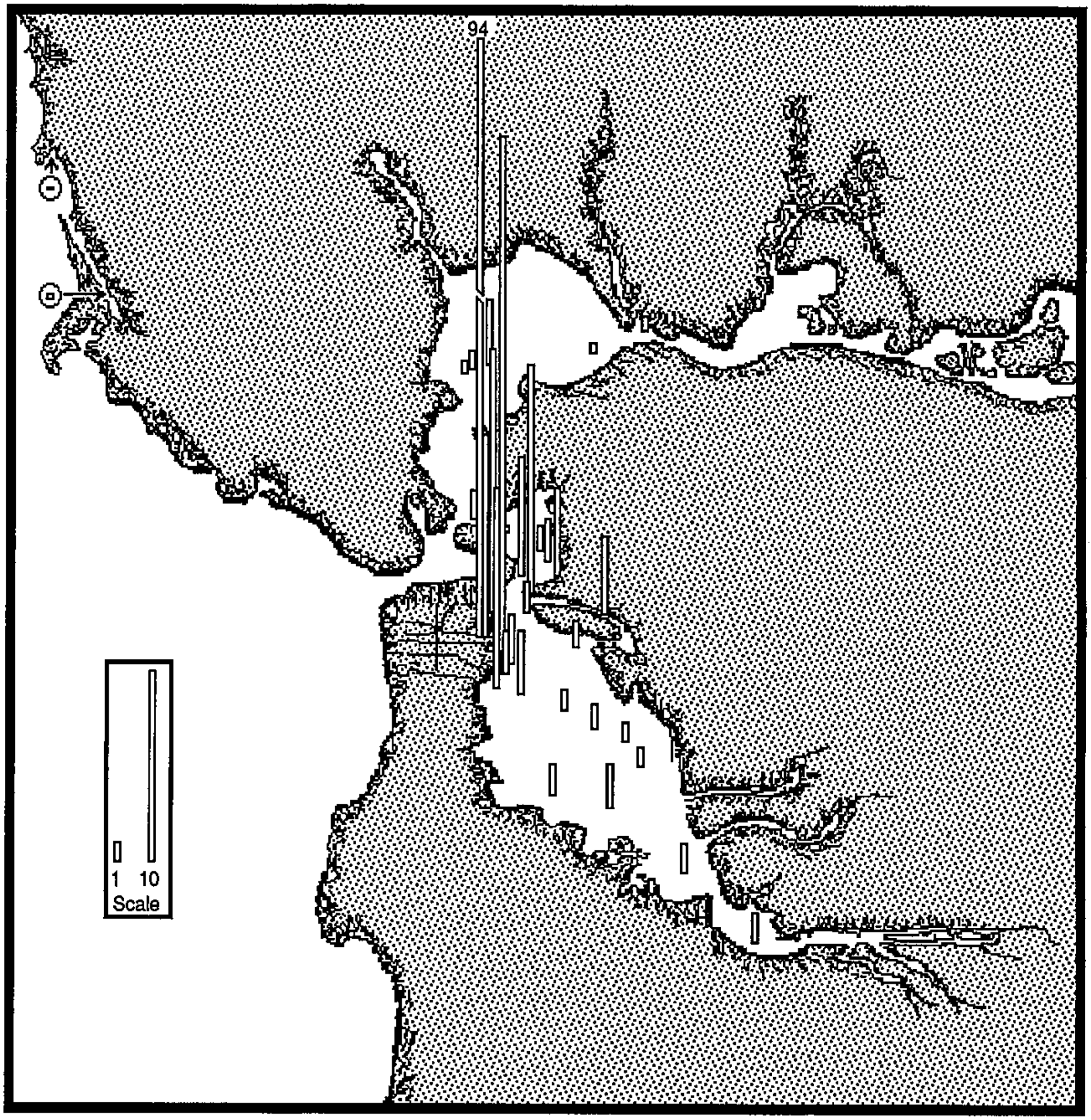


Figure 73. Mean tPAH concentrations, in ppm dw, in the surficial sediments of San Francisco Bay and NOAA's reference sites in Bodega and Tomales bays (in circles) 1985-1986 based on seven common PAHs from the data of NOAA's NS&T Program (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986), Spies (1987, personal communication) and the EPA (Baumgartner et al., unpublished) (sample sizes range from 1 to 4).

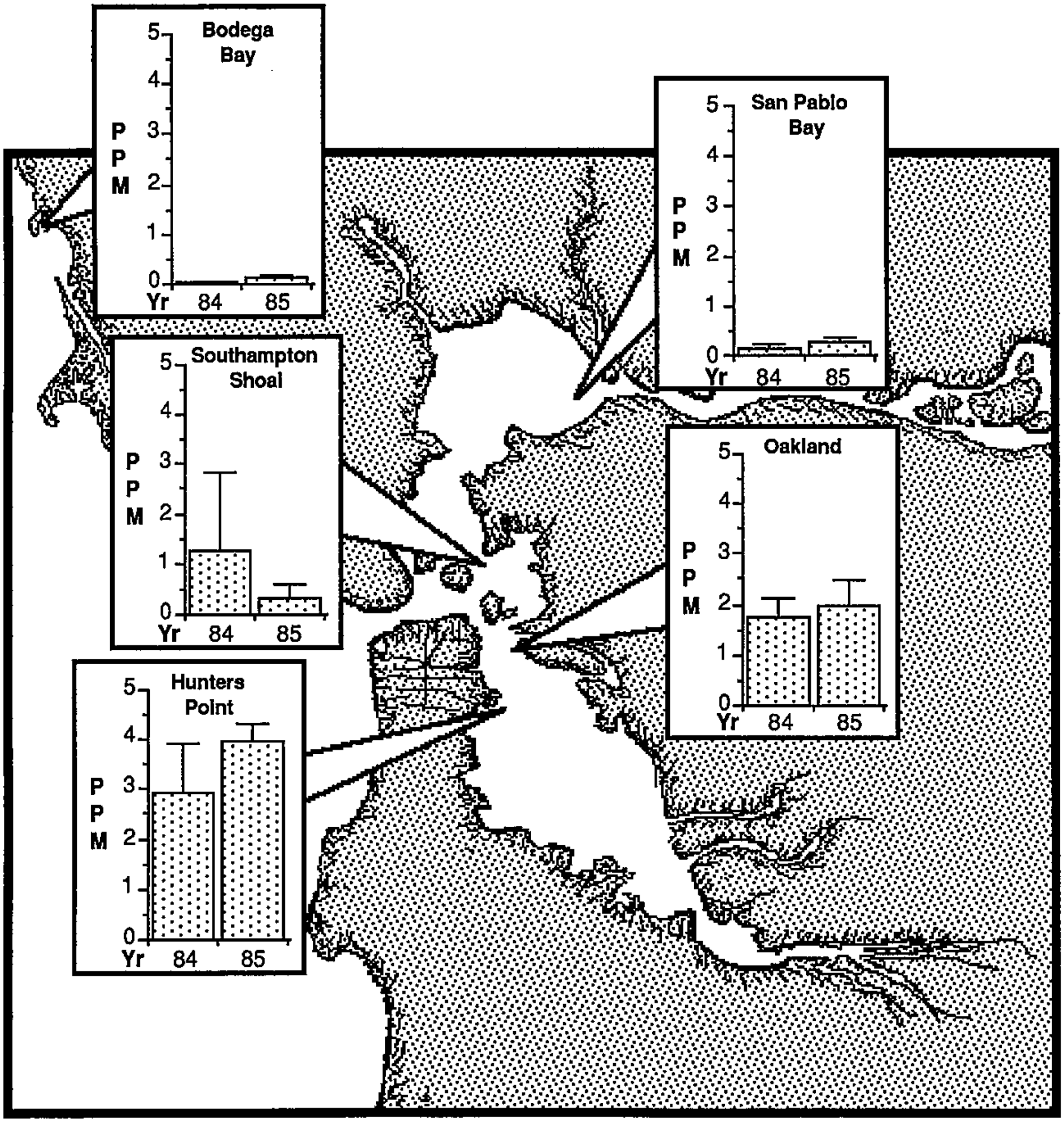


Figure 74. Mean tPAH concentrations and standard deviations, in ppm dw, in surficial sediments at NOAA's NS&T Program sampling sites for 1984 and 1985, based on 18 individual PAHs and three samples per site; the 1985 data for the Oakland site were from the NS&TP Sediment Quality Triad Study (NOAA, 1987a; Chapman et al., 1986).

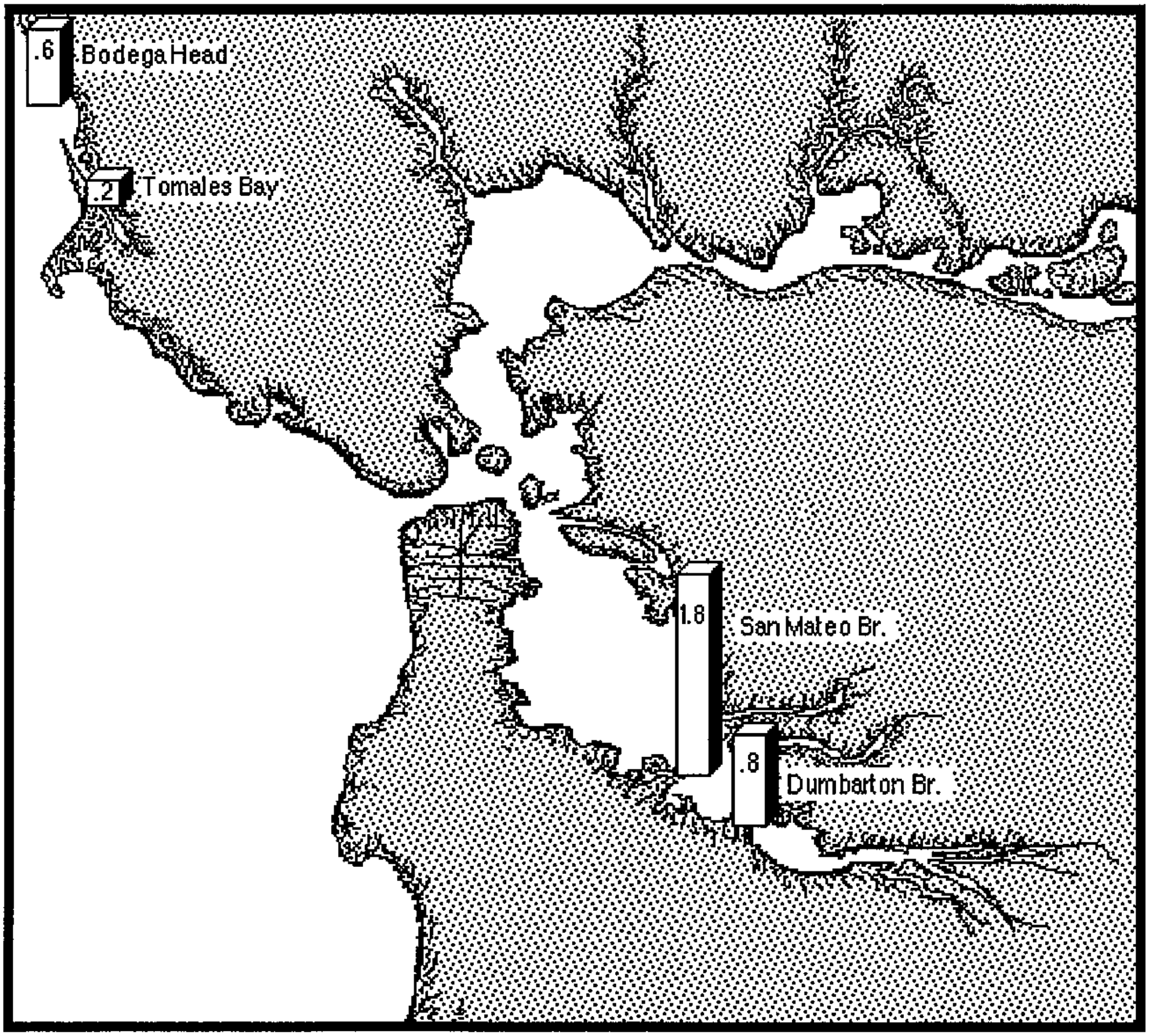


Figure 75. Total PAH concentration in resident mussels (Mytilus edulis, M. californianus) in 1986 (ppm dw) (from Boehm et al., 1987).

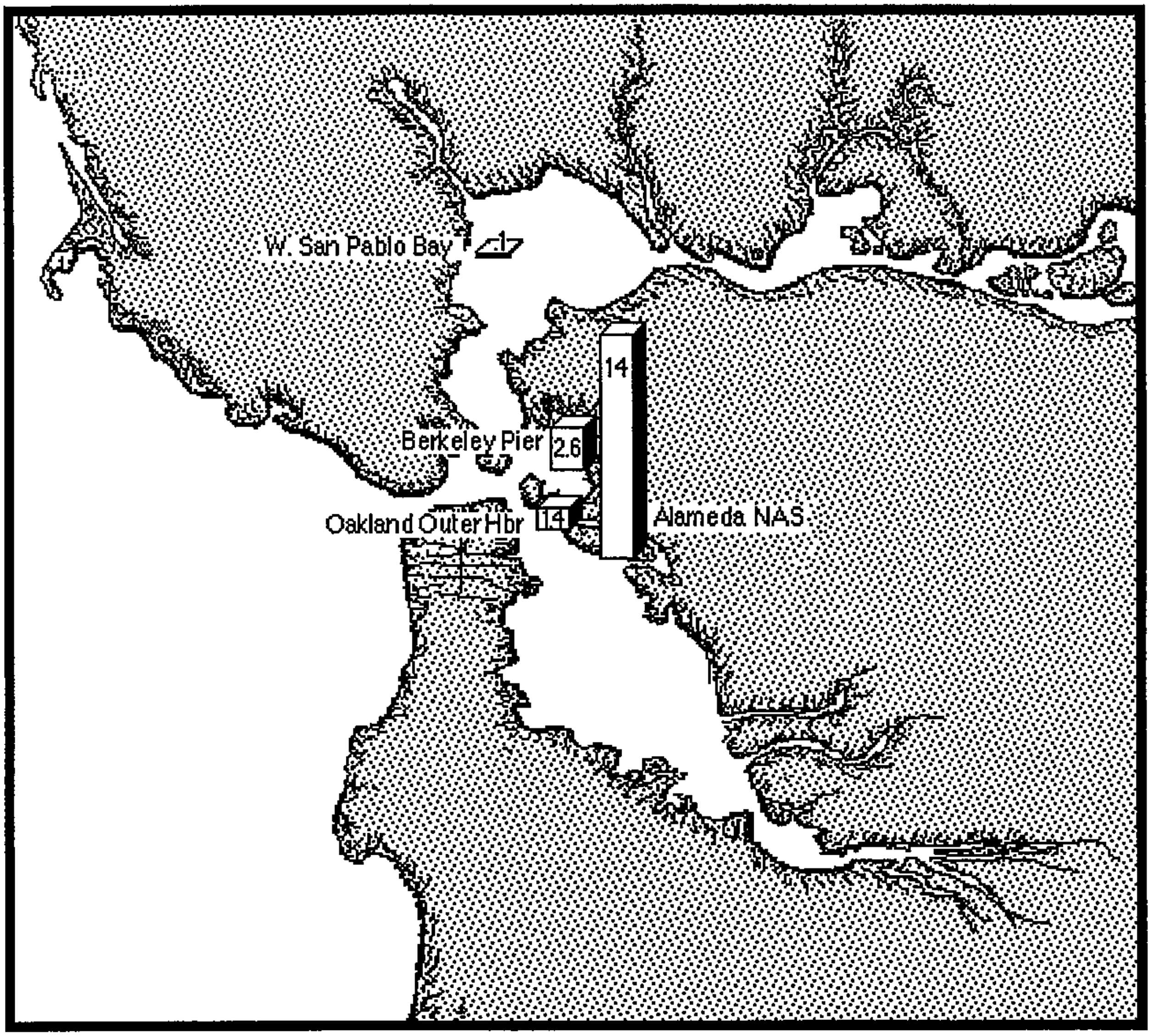


Figure 76. Total PAH and metabolite concentration in starry flounder (Platichthys stellatus) liver sampled in 1984 (ppm ww) (from Spies et al., 1985b).

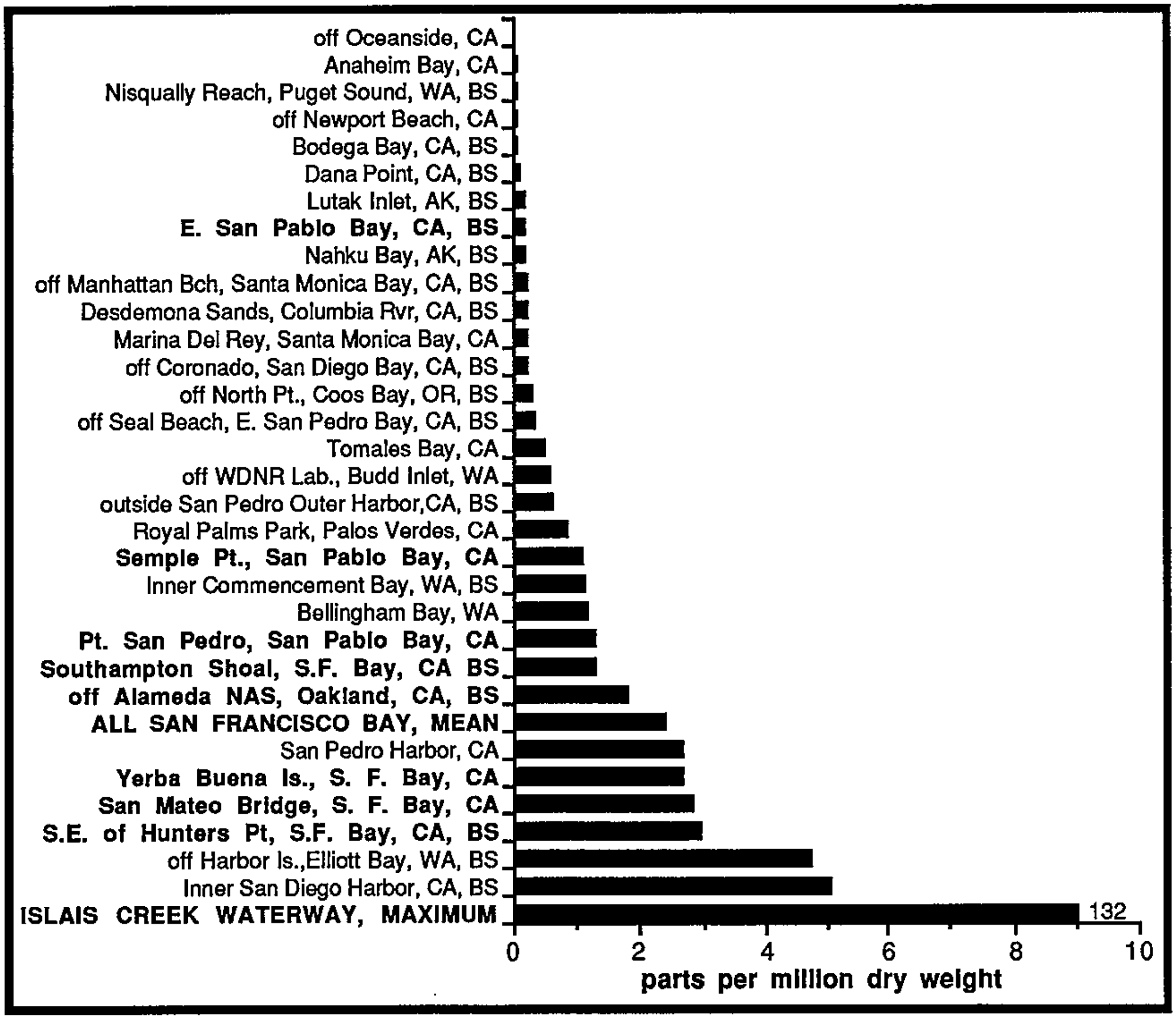


Figure 77. Comparison of PAH concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Table 28), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name) .

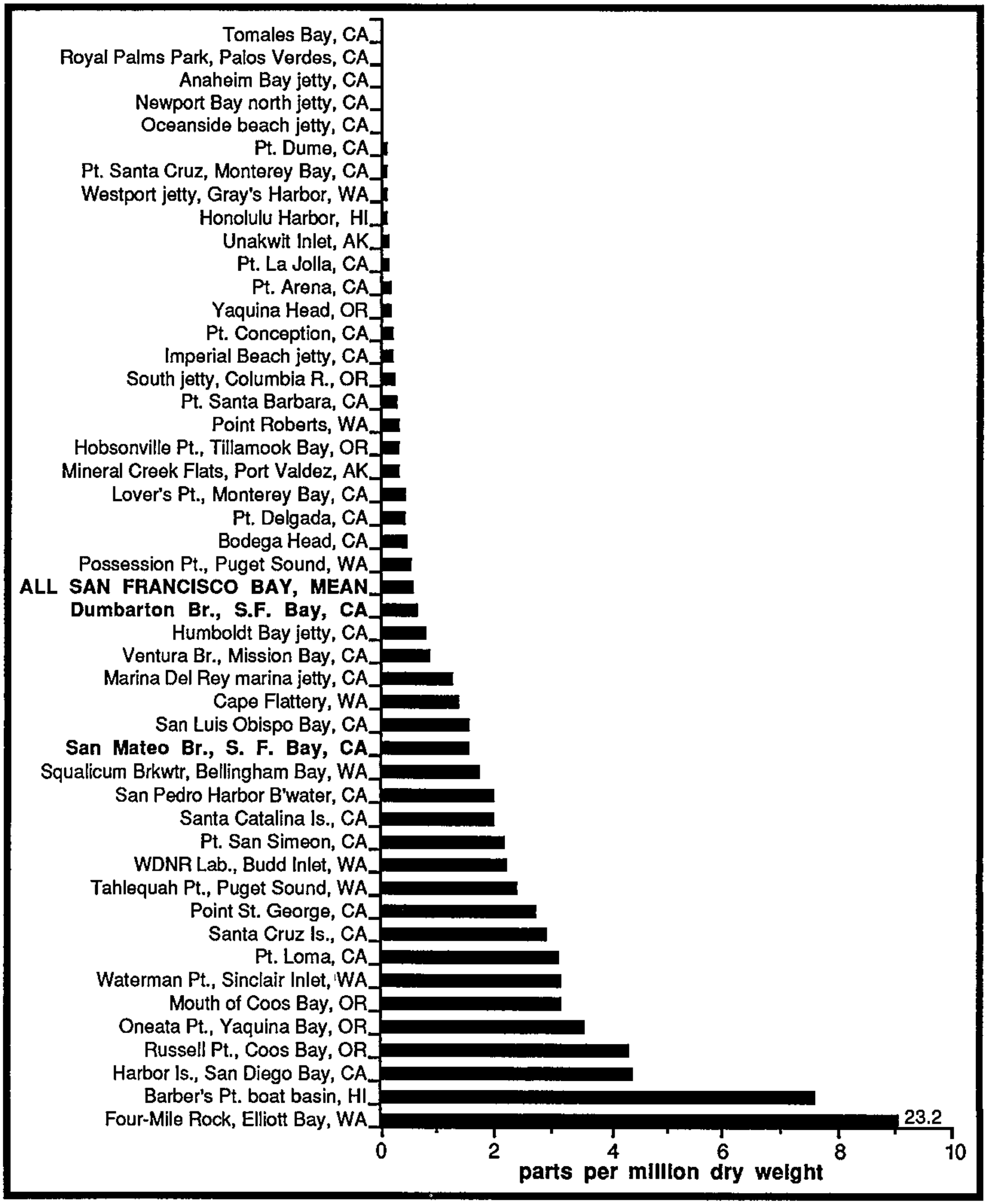


Figure 78. Mean PAH concentrations in resident mussels (Mytilus edulis, M. californianus) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1978-1986) data for San Francisco Bay (Risebrough, et al., 1980 and Boehm et al., 1987). Areas for which historical data are shown are listed in upper-case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

10

GEOGRAPHIC AND TEMPORAL TRENDS IN DDT CONTAMINATION

A. Sediments

Since 1971, the surficial sediments of San Francisco Bay have been intermittently sampled and analyzed for DDT contamination. Analyses have been performed for the isomers of DDT, DDD, and DDE. In this report, the concentrations of these isomers are summed and reported as total DDT (tDDT). Based on the data compiled for this report, the mean concentration of tDDT in the surficial sediments of San Francisco Bay for the period 1971 through 1987 was 7,500 parts per billion (ppb) with a standard deviation of 61,600 ppb (Table 30). However, this mean is heavily skewed because of the data from the severely contaminated Lauritzen Canal. Without the data from the Lauritzen Canal, located in Richmond Harbor, the mean for San Francisco Bay was 100 ppb with a standard deviation of 280 ppb and a range of 0.25 to 1,960 ppb. The median concentration with the Lauritzen Canal data was 10 ppb and without the data the median was 7 ppb.

The data compiled for this report were derived from the sources listed in Table 1. In addition, data were available from an intensive study of the contaminated Lauritzen Canal by Harding Lawson Associates (Frizzell and Davies, 1986).

(1) Geographic Trends

Table 30 presents the grand means, standard deviations, medians, and ranges for the entire Bay, as well as for the basins and the peripheral areas. The results of these calculations with and without the data from Lauritzen Canal are shown. Even excluding the data for the Lauritzen Canal, the peripheral sediments of San Francisco Bay are still noticeably more contaminated with DDT than the basin sediments by a factor of 20, based on the means, (190 vs 9 ppb) or by a factor of 8 when the medians (23 vs 3 ppb) are compared. The basin samples with the lowest tDDT values (0.25 ppb) were taken at the Southampton Shoal and San Pablo Bay sites in 1984 (NOAA, 1987) and the San Pablo Bay site in 1985 (Chapman et al., 1986). Excluding the Lauritzen Canal data, the highest value for peripheral sediments (1,960 ppb) was found off Virginia Street in Berkeley by ANATEC (Kinney and Smith, 1982) in 1980, while the lowest value came from the Islais Creek site in 1985 (Chapman et al., 1986). Total DDT concentrations at the 13 sites sampled in the Lauritzen Canal from 1984 and 1985 ranged from 900 to 765,000 ppb (Frizzell and Davies, 1986).

During 1971 dredging studies, two sediment samples collected from the upper 2.5 feet, from Redwood City Harbor and two surface sediment samples from Alameda NAS were analyzed for DDT by the COE (COE, 1979b). The mean of the four samples was 8.1 ppb and the range was from 3.6 to 15.8 ppb (Table 31). The mean for the Redwood City Harbor samples was 4.1 ppb, while the mean for the Alameda NAS samples was 12.2 ppb.

As part of the COE's intensive dredge study, Serne and Mercer (1975) analyzed a total of 10 sediment samples collected during August 1973 from the upper 60 cm from eight areas for DDT concentrations. The sample values ranged from a minimum of 5 ppb at Pinole Shoal Channel to a maximum of 250 ppb in Oakland Inner Harbor. The overall mean was 71 ppb with a standard deviation of 79 ppb (Table 31).

CH^2M-Hill prepared a report in 1979 for the City and County of San Francisco on the effects of untreated sewage overflows on the eastern portion of south San Francisco Bay (CH^2M-Hill, 1979). Sediments from the upper 10 to 13 cm at 23 sites between China Basin and Brisbane Lagoon were analyzed for DDT. Multiple samples (two to five) were collected at each site. The overall mean concentration of tDDT at the 23 sites was 13 ppb with the means of the individual sites ranging from 2.5 to 140 ppb (Table 31). The highest mean tDDT concentration (140 ppb) was found at the head of the China Basin channel, while the second highest mean (46 ppb) was found at the head of Islais Creek channel. Eight of the sites, including one in China Basin, had means of 2.5 ppb.

ANATEC and Kinnetic Laboratories conducted a monitoring program for the East Bay Municipal Utility District in 1980 and 1981 (Kinney and Smith, 1982). They analyzed 31 samples of the upper 10 cm of sediment from three areas (Point Isabel, San Leandro Creek, and off Virginia Street near Berkeley). The overall mean tDDT concentration for the study was 417 ppb with a standard deviation of 519 ppb and a range of 5 to 1,960 ppb. The means for the individual sampling areas ranged from a low of 7.7 ppb at Point Isabel, to a high of 1,015 ppb off Virginia Street. San Leandro Creek had a mean of 270 ppb. All three areas were found to be significantly different from each other (p=0.05).

In 1986, Spies (1987, personal communication) analyzed 22 samples from 11 sites around the Bay for DDT concentrations. The overall mean for the study was 22 ppb with a standard deviation of 27 ppb and a range from 3 to 97 ppb (Table 31). The site means ranged from 5 ppb in San Pablo Bay (three samples) to 95 ppb in Islais Creek (one sample).

In 1984 and 1985, Harding Lawson Associates conducted a study of DDT contamination in the Lauritzen Canal in Richmond Harbor (Frizzell and Davies, 1986). During the 2 years, they analyzed 13 sediment samples from the upper 1.5 to 3 feet and found an overall mean concentration of 94,400 ppb with a range of from 900 to 765,000 ppb.

The EPA conducted a sediment survey in the south Bay in 1986 and analyzed 11 sediment samples from 10 sites in the Bay for DDT concentrations (Baumgartner et al., unpublished manuscript). The overall mean for the 11 samples was 18 ppb with a standard deviation of 26 ppb and a range of from 1.4 to 91 ppb (Table 31).

Also in 1986, the U. S. Navy had 10 sediment samples from Hunters Point and Treasure Island analyzed for DDT concentrations as part of the *U.S.S. Missouri* homeporting study (U.S. Navy, 1987). All samples analyzed had DDT concentrations below the analytical detection limits; these limits ranged from 6 to 600 ppb (Table 31).

In 1984, the Benthic Surveillance Project (BS) of NOAA's NS&T Program began analyzing samples of the upper 3 cm of sediment for DDT concentrations from four sites in San Francisco Bay: eastern San Pablo Bay, Southampton Shoal, near Oakland off the northwest end of Alameda Island, and southeast of Hunters Point (NOAA, 1987a). Samples from the same sites, with the exception of the site off Oakland, were again analyzed in 1985. The overall mean tDDT concentration, for the 2-year period, was 1.2 ppb with a standard deviation of 0.99 ppb and a range of 0.25 to 4.2 ppb. The site means ranged from 0.40 ppb at the Southampton Shoal site to 2.9 ppb at the site off Oakland (Figure 79). The individual samples with the lowest tDDT concentration (0.25 ppb) were from Southampton Shoal and San Pablo Bay in 1984, while the sample with the highest tDDT concentration (4.2 ppb) was from the Oakland site in 1984. In both 1984 and 1985, samples from a site in Bodega Bay, an area minimally influenced by anthropogenic activities, were also analyzed for DDT concentrations. All the samples had tDDT concentrations below the detection limits, which ranged from 0.1 to 0.2 ppb. The Oakland site was significantly different than the Southampton Shoal and San Pablo Bay (0.82 ppb) sites and the Hunters Point site (1.7 ppb) was significantly different than the Southampton Shoal site (p=0.05). The Bodega Bay site was significantly different than all four of the San Francisco Bay sites (p=0.05).

Also in 1985, NOAA's NS&T Program conducted a Sediment Quality Triad (Triad) study at three sites in San Francisco Bay: western San Pablo Bay, near Oakland off the northwest end of Alameda Island, and in Islais Creek (Chapman et al., 1986). The upper 2 cm were analyzed for toxicity, benthos, heavy metals, and organic contaminants. The overall mean tDDT concentration in the sediments, based on three samples per site, was 1.5 ppb with a range of 0.25 to 3.6 ppb. All three sites were significantly different from each other (p=0.05); the means for the three sites were: San Pablo Bay, 0.37 ppb; Oakland, 1.2 ppb; and Islais Creek, 2.9 ppb (Figure 79).

In 1986, the NS&T Program Mussel Watch Project (MW) analyzed sediment samples for DDT concentrations from four sites in the Bay: off Semple Point, northeast of Point San Pedro, east of Yerba Buena Island, and near the San Mateo Bridge. In addition, sediment samples from a site in Tomales Bay, an area minimally influenced by anthropogenic activities, were analyzed (Boehm et al., 1987). The analyses were carried out on samples of the upper 1 cm of sediment. The overall mean tDDT concentration for the sites in the Bay, based on three samples per site, was 19 ppb with a range of 6.5 to 46 ppb (Table 31). The individual site means ranged from 8.8 ppb at

San Mateo Bridge to 31 ppb at Yerba Buena Island; the Tomales Bay mean was 1.9 ppb (Figure 79). The Yerba Buena site was significantly different than the San Mateo Bridge site and all Bay sites were significantly different than the Tomales Bay site (p=0.05).

When all the NS&T Program data (BS, Triad, MW) for the 3-year period were pooled, the Bay-wide mean for the 10 sites was 6.7 ppb. With the exception of the two most contaminated sites, Oakland (2.0 ppb) and Islais Creek (2.9 ppb), all the Benthic Surveillance and Triad sites were significantly different than all the Mussel Watch sites (p=0.05). The Oakland and Islais Creek sites were significantly different than the least contaminated Benthic Surveillance (Southhampton Shoal (0.40 ppb)) and Triad (San Pablo Bay (0.37 ppb)) sites and the most contaminated Mussel Watch sites, Semple Point (23 ppb) and Yerba Buena Island (31 ppb) (p=0.05). In addition, the Oakland site was significantly different than the Point San Pedro site (11 ppb) and Southampton Shoal was significantly different than Hunters Point (1.7 ppb)(p=0.05). The Bodega Bay site (0.08 ppb) was significantly different than all the other sites including the Tomales Bay site , while the Tomales Bay site was only significantly different than the two most contaminated sites in San Francisco Bay (p=0.05). Figure 79 displays the mean concentrations from the NS&T Program data for the sites sampled in 1984 through 1986.

Figure 80 compares the mean DDT concentrations at the sites sampled by NOAA and Harding Lawson Associates in 1985. In addition to the San Francisco Bay sites depicted, the NOAA reference site in Bodega Bay is also shown. The Lauritzen Canal is clearly the most contaminated area, with a mean DDT concentration in its sediments of 260,700 ppb. The most contaminated site sampled by NOAA in 1985 was Islais Creek, with a mean concentration of 2.9 ppb. When compared to the Bodega Bay reference site, the sediments from San Francisco Bay sites (excluding those in Lauritzen Canal) have a mean tDDT concentration ranging from 8 to 58 times higher than that found in Bodega Bay sediments.

As mentioned above, in 1986 several groups collected and analyzed sediment samples from the Bay for DDT contamination; Figure 81 compares the results from these studies (note the columns in Figures 79, 80, and 81 are drawn to different scales). Based on the data depicted in Figure 81, the most contaminated area in the Bay was Islais Creek, with a single sample value of 95 ppb. The second most contaminated site was northeast of Coyote Point in south Bay with a single sample value of 91 ppb. Other areas of relatively high DDT contamination were the Alameda estuary (mean of three samples = 45 ppb) and India Basin (mean of two samples = 38 ppb). Figure 81 indicates that Treasure Island, sampled by the Navy, also had a relatively high mean (62 ppb), but this is a result of relatively high detection limits, with all the values falling below these limits and the resulting mean being based on half the detection limits. The least contaminated area was the east central area of south Bay with tDDT concentrations ranging from 1-3 ppb. When compared to the reference site in Tomales Bay (1.9 ppb), the sediments from San Francisco Bay sites sampled in 1986 were from 1 to 50 times more contaminated with DDT than the Tomales Bay sediments.

(2) Temporal Trends

There are no data available to assess long-term temporal trends in DDT contamination in sediments in the Bay.

Because of the intermittent nature of the available data on DDT contamination of San Francisco Bay sediments, it is difficult to determine whether or not there are any trends of increasing or decreasing DDT contamination. Table 31 lists the means, standard deviations, medians, and ranges of DDT concentrations by year and sampling group. The variation in the mean DDT concentrations is more a result of the geographic area sampled by each survey than the year sampling took place. There is also variability associated with the inter-laboratory differences in the analytical methods. The Harding Lawson Associates' data are solely from the Lauritzen Canal and the ANATEC/Kinnetic Laboratories data are from sites associated with sewage overflows.

At this time, the only way to determine if there are any temporal trends is to look at individual sites that have been sampled in more than one year by the same group. Figure 82 compares data from NOAA's Benthic Surveillance sites for 1984 and 1985. The NOAA data show little change between 1984 and 1985, with tDDT concentrations increasing significantly at the Hunters Point and San Pablo Bay sites and decreasing significantly at the Oakland site (based on one-tailed T-test of log transformed data, p=0.01). However, the time intervals for this data set are too short to accurately determine if temporal changes have occurred.

B. Biota

The biota of San Francisco Bay have been well sampled for their DDT content. Since 1965, 25 surveys have analyzed DDT compounds in fish, crustaceans, or bivalves (Table 2). The data below are sums of the DDT, DDD, and DDE isomers and expressed as tDDT.

Fish caught from San Francisco Bay have yielded a total of 448 samples of flesh (muscle), liver, gonad, or other tissue for DDT analyses. The species sampled most frequently (127 samples) for DDT analysis has been starry flounder (*Platichthys stellatus*), followed by a total of 113 samples of striped bass (*Morone saxatilis*).

By pooling all data from 1975 through 1986 for tDDT concentrations in mussels (*Mytilus edulis, M. californianus*) sampled in the San Francisco Bay system (189 samples), a grand mean DDT concentration has been 0.33 ppm, with a range of 0.01 to 22.47 ppm (Table 32). Means and ranges in concentrations reported for mussels by individual surveys are summarized in Figure 83 and compared to the grand mean for the Bay.

(1) Geographic Trends

Highest levels of DDT appear to have occurred in mussels (*Mytilus spp.*) from the Santa Fe Channel (Richmond Harbor). Mussels sampled from Tomales Bay and Bodega Head have contained very low concentrations of tDDT compared to San Francisco Bay, where mean levels are elevated above these reference areas by a factor of 15.

In 1968, several species of bivalves (*Ostrea lurida, Modiolus demissus, Corbicula fluminea, Crassostrea gigas*) collected at eight sites from Suisun Bay to Guadalupe Slough by the National Pesticide Monitoring Program (NPMP) were analyzed for DDT contamination (Butler, 1973; Butler et al., 1978). They showed highest levels of tDDT in clams (*C. fluminea*) from the Sacramento-San Joaquin Delta (0.76 ppm ww, approximately 6.7 ppm). Lowest DDT levels were found in ribbed horse mussels (*M. demissus*) from the mouths of the Napa and Petaluma Rivers (approximately 0.1 ppm ww, or .88 ppm dw) and Coyote Point in south Bay. A pattern of decreasing concentrations south from Suisun Bay was evident.

The sampling of clams (*Tapes semidecussata* or *Mya arenaria*) from 15 sites in central, south, and San Pablo bays in 1972 by Shimmin and Tunzi (1974) showed highest levels of tDDT occurred at Burlingame and San Leandro Bay (approximately 0.024 ppm ww or 0.02 ppm dw). All other sites in south, central, and San Pablo bays produced clams with relatively low tDDT concentrations (0.05 to 0.21 ppm). None of their sites was located where NPMP had sampled previously.

Girvin (1975) found a mean tDDT concentration of 0.19 ppm in *Mytilus edulis* at three sites in south and central bays (Figure 83). Also in 1975, Anderlini et al. (1975b) detected a mean of 0.06 and a range of 0.01 to 0.09 ppm tDDT in 93 samples of transplanted *Mytilus edulis* at two sites, one in central Bay and one near the EBMUD outfall (Figure 83).

In 1976, mussels (*Mytilus edulis*) from 27 sites from the Carquinez Bridge to Redwood City were sampled by Risebrough et al. (1978). The highest level of tDDT was detected at a site in south Bay (0.31 ppm). Mussels from sites in south Bay generally contained higher levels of DDT than mussels from central Bay, which contained higher levels of tDDT than mussels from San Pablo Bay. The range in concentration was 0.04 to 0.31 ppm and the mean for the survey was 0.12 ppm (Figure 83).

Bay mussels (*Mytilus edulis*) were sampled in 1980 at eight sites in the Bay by California Mussel Watch (Hayes et al., 1985) and by McCleneghan et al. (1982). Highest levels of tDDT found by McCleneghan were in mussels from peripheral and basin sites at Point Isabel (0.58 to 0.84 ppm). Mussels from Bayshore Lagoon also contained high levels of tDDT (0.474 ppm). Other south Bay sites at Burlingame, Coyote Point, Redwood

Creek, and Point Richmond had less than 0. 2 ppm. Mussels sampled by McCleneghan showed differences in DDT levels between all sites to be significant, except between Burlingame and Coyote Point (p=0.05). Except for the single very high concentration at Angel Island (2.57 ppm) in 1980, the California Mussel Watch data were relatively similar each year until 1985 (Figure 83).

Highest concentrations of DDT in fish have been detected in samples of striped bass (Whipple, 1984; Whipple et al., 1987). Concentrations of DDT in striped bass liver have reached a maximum of 7.48 ppm ww in a fish caught off Antioch in 1981. Levels of DDT in flesh have been highest in fish from the Sacramento River in 1973 (6.94 ppm ww) (Stout and Beezhold, 1981). Concentrations of DDT in gonads were as high as 13.62 ppm ww in a striped bass from Antioch in 1981.

The NOAA NS&T Program surveyed livers of white croaker (*Genyonemus lineatus*) and starry flounder (*Platichthys stellatus*) from four sites in San Francisco Bay, and a site in Bodega Bay in 1984 (NOAA, 1987a). Except in Bodega Bay, all the fish had between 1.1 and 1.5 ppm tDDT. Highest levels of DDT were detected in livers of white croaker collected off Oakland (1.51 ppm) (Table 33). Lowest levels were detected in starry flounder livers from San Pablo Bay (1.00 ppm) and in white croaker livers from Bodega Bay (0.13 ppm). None of the differences in DDT concentrations between sites was significant (p=0.05). In 1985, most of the sites were resampled. In 1985, highest levels of tDDT were detected in livers of starry flounder from Southhampton Shoal (1.90 ppm). Lowest levels were detected in starry flounder from San Pablo Bay (1.32 ppm) and white croaker, English sole (*Parophrys vetulus*), and starry flounder from Bodega Bay (0.34, 0.16, and 0.98 ppm, respectively). Again, differences between sites in tDDT levels in starry flounder were not significant (p=0.01).

In 1985 and 1986, the California Mussel Watch Program surveyed DDT in resident and transplanted mussels (*Mytilus edulis, M. californianus*) from 11 sites in San Francisco Bay and resident mussels from Bodega Head (Figure 84) (Hayes and Phillips, 1986). Highest concentrations of tDDT in 1985 were detected in mussels transplanted to a site in Richmond Inner Harbor (10.7 ppm). Resident mussels taken in 1986 from one site in Santa Fe Channel in Richmond Harbor contained 22.47 ppm tDDT. Lowest levels of tDDT were detected in mussels transplanted to Point Pinole in San Pablo Bay (0.04 ppm). Total DDT levels in mussels from Bodega Head were 0.01 ppm in 1985. Because of the samples from Richmond Inner Harbor, the ranges in values for 1985 and 1986 were very wide (Figure 83) and noticeably different from those reported for previous years.

In 1986, the NS&T Program sampled resident mussels (*Mytilus edulis*) from two sites in San Francisco Bay and from a site each at Bodega Head (*M. californianus*)) and in Tomales Bay (*M. edulis*) (Boehm et al., 1987) (Figure 84). Highest concentrations of DDT were detected in mussels from Dumbarton Bridge (0.32 ppm). Lowest levels of DDT were detected in mussels from Tomales Bay (0.01 ppm). Concentrations of tDDT in mussels were significantly different between the two reference sites (Bodega Head and Tomales Bay) and two sites in the Bay (Dumbarton Bridge and San Mateo Bridge) (p=0.05). The two sites in the Bay were not significantly different from each other (p=0.05).

The sampling of mussels by the NS&T Program was conducted at sites that had been previously occupied by other surveys. Results of tDDT analyses by the NS&T Program are generally comparable to those of others. From 1976 through 1983, other investigators (Hayes et al., 1985; Risebrough et al., 1978) found mussels at the San Mateo Bridge contained a mean concentration of 0.06 ppm with a range of 0.03 to 0.13 ppm. The NS&T Program detected 0.13 ppm at this site. The Dumbarton Bridge has also been sampled by Hayes et al. (1985) and Risebrough et al. (1978). Results of these previous surveys showed a mean of 0.15 ppm in mussels between 1976 and 1983, with a range of 0.06 to 0.27 ppm. The NS&T Program detected 0.32 ppm in mussels from the same site. Sampling of mussels from Tomales Bay has been conducted by Butler et al. (1978) and Hayes et al. (1985). The mean level of tDDT in mussels between 1979 and 1982 was 0.03, with a range of 0.03 to 0.04. The NS&T Program detected 0.01 ppm in mussels collected in 1986 from Tomales Bay. Sampling at Bodega Head from 1977 through 1986 by the California Mussel Watch Program (Hayes et al., 1985; Hayes and Phillips, 1986, 1987) resulted in a mean level of tDDT in mussels of 0.02 ppm, with a range from less than 0.005 to 0.11 ppm. The NS&T Program detected 0.03 ppm in mussels from Bodega Head.

(2) Temporal Trends

Total DDT levels have been analyzed in clams (*Tapes spp.*) at two sites by three surveys between 1972 and 1980. Sampling by the U.S. EPA (Shimmin and Tunzi, 1974), Girvin et al. (1975), and McCleneghan et al. (1982) showed tDDT were 0.16 ppm in 1972, 0.13 ppm in 1975, and 0.06 ppm in 1980 at Albany Hills. At Foster City, the concentrations were 0.21 in 1972, 0.07 in 1975, and 0.19 ppm in 1980.

The monthly sampling of a variety of resident bivalves (*C. fluminea, O. lurida, M. demissus,* and *C. gigas*) by the NPMP provides a unique record of DDT levels over 10 years at eight sites in the San Francisco Bay system (Figure 85). Total DDT levels declined between 1966 and 1977 at all sites. In the first year of sampling (1966, 1967, or 1968) tDDT levels were as high as 1.34 ppm ww. In the last year of sampling, 1977, levels of tDDT were below the detection limit of 0.03 ppm ww at most sites.

Total DDT in resident mussels (*Mytilus spp.*) has been measured frequently between 1976 and 1986 by three surveys at Bodega Head or Tomales Bay (Farrington et al., 1982; Hayes et al., 1985; Hayes and Phillips, 1986, 1987). Sampling of mussels in Tomales Bay shows no trend in tDDT levels between 1977 and 1982; values ranged from 0.03 to 0.04 ppm. When Tomales Bay mussels were sampled in 1986 by the NS&T Program, the tDDT concentration was <0.01 ppm. At Bodega Head, tDDT levels peaked in 1981 at 0.03 ppm and declined to 0.006 ppm in 1985. Analysis of tDDT levels in mussels at Bodega Head over time indicates that mean tDDT levels in 1982 were significantly different than tDDT levels measured in 1985 ($p=0.05$). In 1986, the NS&T Program detected 0.03 ppm at that site, similar to the value for 1981. The sampling of resident mussels at Coyote Point shows tDDT levels to have declined slightly between 1975 and 1980, from 0.025 ppm ww to 0.01 ppm ww.

Transplanted mussels (*Mytilus californianus*) have been resurveyed by the California Mussel Watch Program at three to seven sites in the Bay since 1980 (Hayes et al., 1985; Hayes and Phillips, 1986, 1987). Concentrations of tDDT have been variable at most sites, with slight declines occurring since 1981 at Point Pinole, Treasure Island, and the Redwood Creek Mouth. Mussels transplanted to Angel Island have shown a decline in tDDT levels since 1980, from 2.57 ppm to 0.21 ppm by the end of 1982.

Stevens (1977) summarized the mean concentrations of tDDT in striped bass (*Morone saxatilis*) flesh sampled by California Department of Fish and Game in the Sacramento-San Joaquin Delta from 1964 through 1976. The mean concentrations were 0.62 and 0.54 ppm in 1964 and 1965, respectively, peaked at 1.72 ppm in 1969 and at 1.80 ppm in 1972, then decreased to 0.21 and 0.12 ppm in 1975 and 1976. Striped bass from Suisun Bay or San Joaquin River have been sampled three times between 1977 and 1984 for DDT levels in liver and gonadal tissues (Whipple,1984). Levels of tDDT were highest in 1981 in both tissue types. Any differences between years were not significant ($p=0.05$). The data record for DDT in striped bass is larger than that discussed here, but the data are inconsistent in the tissues analyzed, the age of the fish, the analytical methods, and the sites sampled (Demarest, 1987).

Data for DDT in the crab *Cancer magister*, summarized by Demarest (1987), are available for 1969 through 1976 for samples of various body parts and from various sites in the Bay. No clear pattern of change in concentration is apparent from the data over this time period because of the inconsistencies in the data. However, a range of 0.01 to 0.08 ppm tDDT in whole crabs at two sites in central Bay and a range of 0.27 to 0.32 ppm tDDT in the meat at a site in San Pablo Bay in 1969 samples may exceed the range (≥0.002 to ≥0.02 ppm) reported for flesh in samples from unspecified sites in the San Francisco and San Pablo bays collected in 1975 and 1976.

C. Summary

The levels of DDT contamination in the sediments of San Francisco Bay are significantly higher than those found at the reference sites in Bodega and Tomales Bays. With the exception of a few isolated hot samples (Spies' San Pablo Bay site in 1983 and the EPA site northeast of Coyote Point in 1986), the basins of the Bay are significantly less contaminated than the peripheral areas. The Lauritzen Canal at Richmond is extremely highly contaminated.

Due to the intermittent nature of tDDT sampling over the years, no strong conclusion can be drawn concerning the existence of increasing or decreasing tDDT concentrations in sediments. However, based on the limited data available (in particular Spies' data for 1984 and 1985) there may be a trend of decreasing levels of tDDT in the sediments of San Francisco Bay.

Generally, tDDT concentrations in clams have historically been highest in the Suisun Bay/Delta area as compared to the other basins. Concentrations have been lowest in San Pablo Bay. Some high values have also occurred in the Petaluma River, Alviso Slough, and Guadalupe Slough. The single highest concentration was recently detected in mussels from the Santa Fe Channel of Richmond Inner Harbor. Compared to the reference mussels at Bodega Head (0.02 ppm), the overall mean concentration in mussels (0.33 ppm) in the Bay is elevated by a factor of about 10. The highest concentration seen at the Santa Fe Channel site was elevated nearly a thousandfold over the Bay-wide grand mean. The tDDT concentrations in fish have been relatively similar at all sites, however they have been slightly lower in San Pablo Bay than in the Sacramento-San Joaquin Delta. Both the mussels and fish often have had lower concentrations in San Pablo Bay than in the other basins. Recent samples of fish from the Oakland/Berkeley/Richmond area often exceeded those from San Pablo Bay in tDDT concentration.

Data from the late 1960s to the late 1970s show steady decreases in tDDT concentrations in striped bass flesh, resident oysters, clams, and mud-dwelling mussels. However, more recent data from resident bay mussels and transplanted coastal mussels often show a peak in 1981, followed by a steady decline to the present. Recent data from striped bass may also indicate a peak in 1981, but the data record is inconsistent, very small, and short. Data available thus far for starry flounder and other species of fish are inconclusive regarding temporal trends.

Historical mean concentrations of tDDT in sediments sampled from 1971 through 1986 in San Francisco Bay are compared in Figure 86 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper-case print. The NS&T Program 1984 Benthic Surveillance Project sites in the Bay are in bold, lower-case print, designated as "BS." The 1986 Mussel Watch Project sites in the Bay are in bold, lower-case plain print. Pacific Coast NS&T Program sites are in plain print; the Benthic Surveillance Project sites are designated as "BS." The overall historical mean for the Bay (110 ppb, excluding Lauritzen Canal) and all peripheral areas (190 ppb, excluding Lauritzen Canal) ranked relatively high compared to the NS&T Program sites. These historical means were exceeded only by three of the NS&T Program site means--all from southern California sites. The extremely high levels in Lauritzen Canal are readily apparent. However, among 1984 and 1986 NS&T Program sampling sites, only two in the Bay (off Yerba Buena Island and off Semple Point) ranked in the top ten, and the concentrations there were considerably lower than the historical levels. The remaining NS&T Program sites in the Bay ranked 12th through 30th. The two reference sites, Tomales Bay and Bodega Bay, ranked 21st and 29th, respectively.

The historical mean concentrations of tDDT in mussels collected in San Francisco Bay from 1972 through 1986 are compared in Figure 87 with means from three samples of mussels each from NS&T Program Pacific Coast sites sampled in 1986. The historical areas are listed in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located in the Bay are listed in bold print. The grand historical mean for the Bay (0.33 ppm) was relatively high, exceeded by only three NS&T Program site means. Mussels from Richmond Harbor exceeded all others in tDDT concentrations. The Dumbarton Bridge NS&T Program site was relatively contaminated, ranking fourth among the 1986 sites. The other NS&T Program site in the Bay at the San Mateo Bridge ranked 26th. The reference sites, Tomales Bay and Bodega Head, ranked 44th and 27th, respectively.

Table 30. Means, standard deviations, medians, and ranges of tDDT concentrations in surficial sediments of San Francisco Bay, based on data collected by many investigators from 1971 through 1987 (ppb dw).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	7500	61600	10	0.25 - 765000	166
TOTAL DATA W/O LAURITZEN CANAL	100	280	7	0.25 - 1960	153
PERIPHERY	13600	82900	32	2.20 - 765000	91
PERIPHERY W/O LAURITZEN CANAL	190	380	23	2.20 - 1960	78
BASIN	9	15	3	0.25 - 91	75

Table 31. Means, standard deviations, medians, and ranges of tDDT concentrations in the surficial sediments of San Francisco Bay from 1971 through 1987 based on all available data (*based on site means only) (** all values were below detection limits (6-600 ppb) and one half the detection limits were used for the calculations) (ppb dw)

SOURCE	YEAR	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
CORPS OF ENGINEERS	1971	8.1	5.6	6.5	3.6 - 15.8	4
SERNE & MERCER	1973	71.2	79.3	39.5	5.0 - 250	10
CH2M-HILL*	1979	13.1			2.5 - 140	23
ANATEC	1980	488	590	190.0	5.0 - 1960	22
ANATEC	1981	245	223	230.0	9.0 - 650	9
HARDING LAWSON ASSOCIATES	1984	20500	21200	20200	900 - 31900	9
NOAA BENTHIC SURVEILLANCE	1984	1.2	1.2	0.9	0.25 - 4.2	12
NOAA BENTHIC SURVEILLANCE	1985	1.2	0.7	1.4	0.35 - 2.2	9
HARDING LAWSON ASSOCIATES	1985	260700	344400	124800	28000 - 765000	4
NOAA SEDIMENT QUALITY TRIAD	1985	1.5	1.2	1.1	0.25 - 3.6	9
NOAA MUSSEL WATCH	1986	18.7	11.9	13.9	6.5 - 45.9	12
SPIES	1986	22.5	26.6	12.5	3.0 - 97.0	22
EPA	1986	17.8	26.1	6.4	1.4 - 91.3	11
U.S. NAVY**	1986	46.2	89.9	21.0	3.0 - 300	10
BODEGA BAY	85-86	0.08	0.08	0.04	0.04 - 0.25	6
TOMALES BAY	1986	1.91	0.45	1.99	1.42 - 2.32	3

Table 32. Means, medians, and ranges in concentration of tDDT in mussels (Mytilus edulis or Mytilus californianus), collected by many investigators during 1975-1986, in basins and peripheral areas of San Francisco Bay (ppm, dw).

AREA/SITE		MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY						
	BASIN	0.06	-	-		1
SAN PABLO BAY						
	BASIN	0.10	0.06	0.09	<0.02 - 0.23	13
	PERIPHERAL-MARE ISLAND STRAIT	0.07	-	-		1
CENTRAL BAY						
	BASIN	0.12	0.28	0.06	0.01 - 2.6	86
	PERIPHERAL-RICHMOND HARBOR	6.75	8.65	3.35	0.26 - 22.47	6
	POINT ISABEL	0.74	0.14	-	0.64 - 0.83	2
	ALL PERIPHERAL	5.25	7.82	1.26	0.26 - 22.47	8
SOUTH BAY						
	BASIN	0.10	0.09	0.07	0.01 - 0.55	66
	PERIPHERAL-ALAMEDA YACHT	0.14	-	-	-	1
	OAKLAND INNER HARBOR	0.13	0.07	0.13	0.05 - 0.22	4
	OAKLAND OUTER HARBOR	0.13	-	-	-	1
	BAYSHORE LAGOON	0.47	0.04	-	0.44 - 0.5	2
	REDWOOD CREEK	0.11	0.05	0.10	0.06 - 0.2	6
	ALL PERIPHERAL	0.17	0.14	0.13	0.05 - 0.5	14
ALL SAN FRANCISCO BAY		0.33	1.84	0.07	0.01 - 22.47	189
TOMALES BAY		0.02	0.02	0.03	0.01 - 0.04	7
BODEGA HEAD		0.02	0.02	0.02	0.01 - 0.11	17

Table 33. Total DDT (ppm dw) in fish liver based on NOAA NS&T Program data for 1984 and 1985 (NOAA, 1987a).

SITE/SPECIES	TOTAL DDT 1984	1985
SAN PABLO BAY		
STARRY FLOUNDER	1.001	1.325
SOUTHHAMPTON SHOAL		
STARRY FLOUNDER	1.2	1.905
OAKLAND		
WHITE CROAKER	1.514	
HUNTERS POINT		
STARRY FLOUNDER	1.308	
WHITE CROAKER		1.557
BODEGA BAY		
STARRY FLOUNDER	1.141	0.985
WHITE CROAKER	0.133	0.337
ENGLISH SOLE		0.16

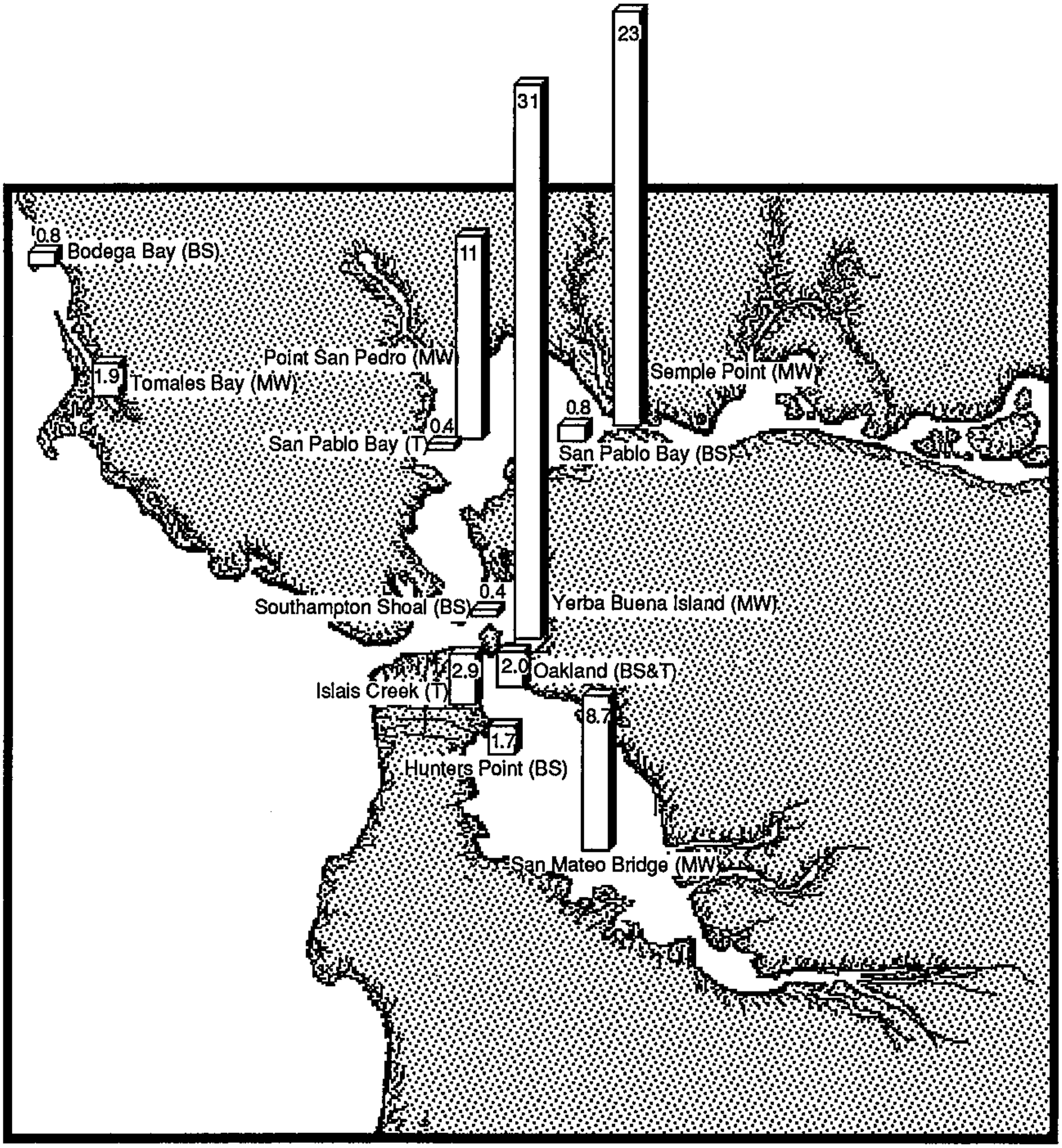


Figure 79. Mean tDDT concentration, in ppb dw, in the surficial sediments at the NOAA NS&T Program sites for 1984-86 (BS=Benthic Surveillance, MW=Mussel Watch, T=Sediment Quality Triad) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986).

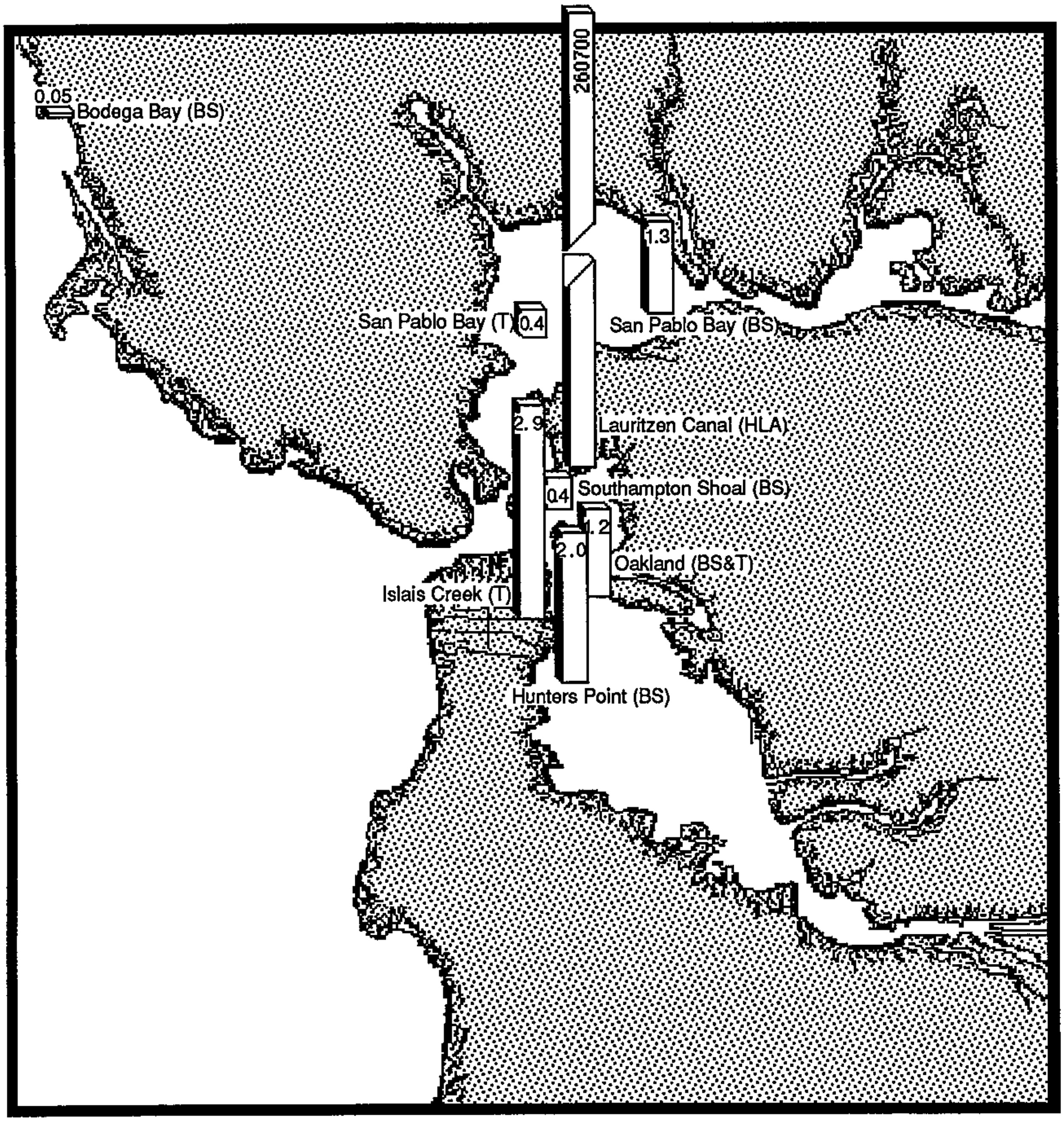


Figure 80. Mean tDDT concentrations in the surficial sediments of San Francisco Bay for 1985 based on data from NOAA's NS&T Program Benthic Surveillance (BS) and Sediment Quality Triad (T) and Harding Lawson Associates (HLA) (ppb dw) (NOAA, 1987a; Chapman et al., 1986; Frizzell and Davies, 1986).

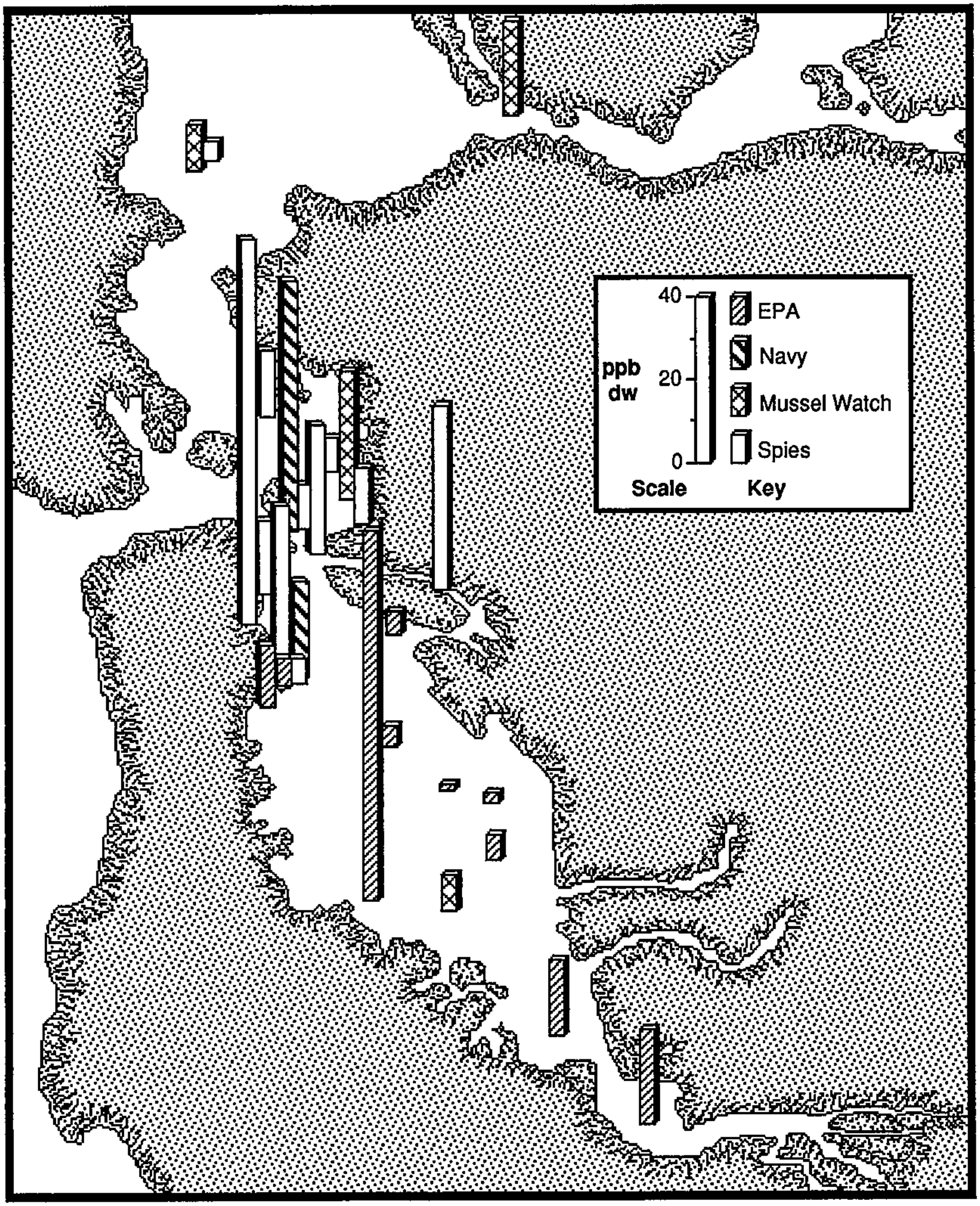


Figure 81. Mean tDDT concentrations in the surficial sediments of San Francisco Bay for 1986 based on the data of the U. S. Navy (1987), EPA (Baumgartner, unpublished manuscript), NOAA Mussel Watch (Boehm, *et al.*, 1987), and Spies (1987, personal communication).

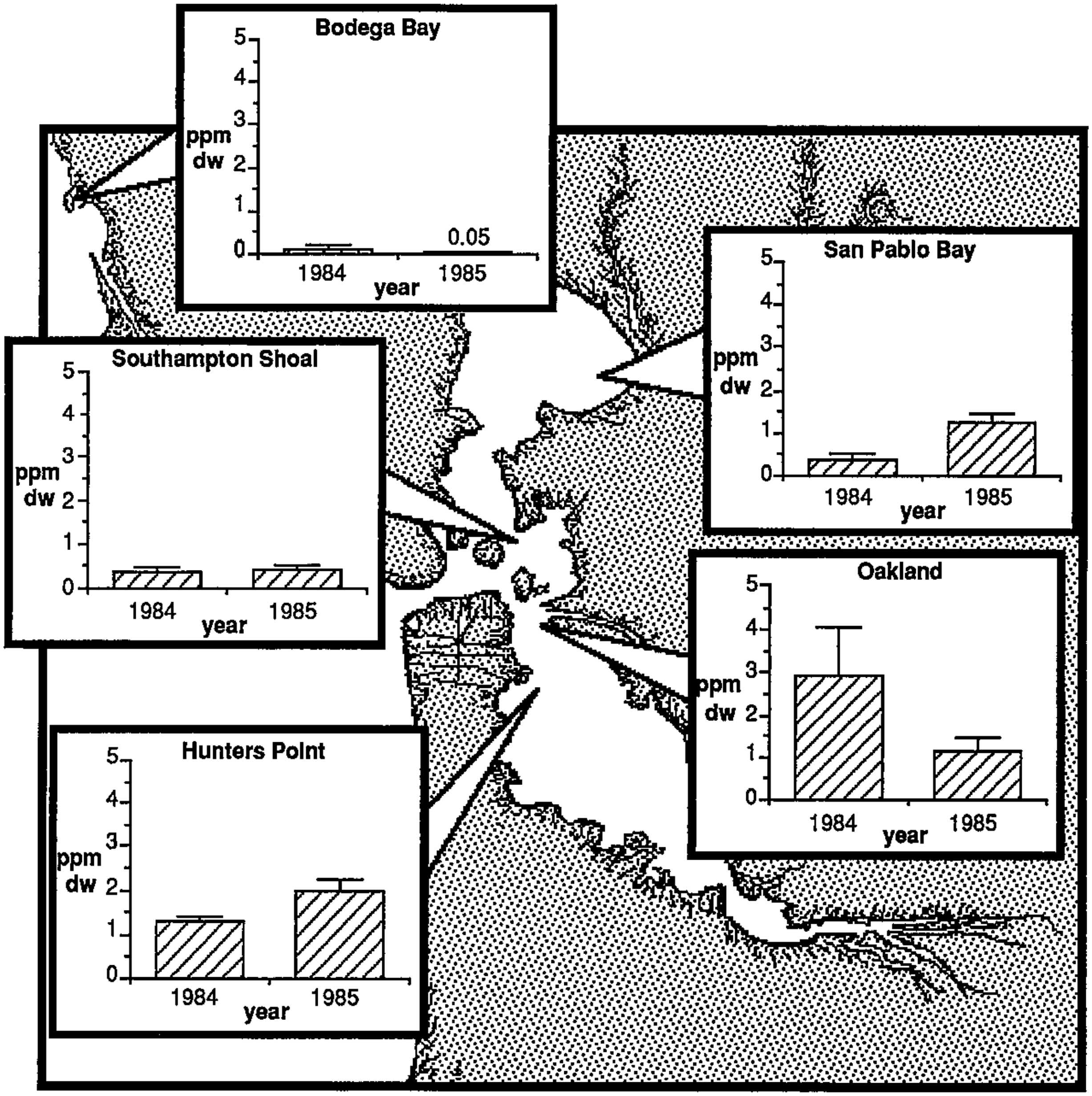


Figure 82. Yearly mean tDDT concentrations in the surficial sediments at the NOAA NS&T Program Benthic Surveillance Project (NOAA, 1987a) sites in San Francisco Bay and Bodega Bay. Note the 1985 data for the Oakland site are from the NS&T Program Sediment Quality Triad Project (Chapman *et al.*, 1986).

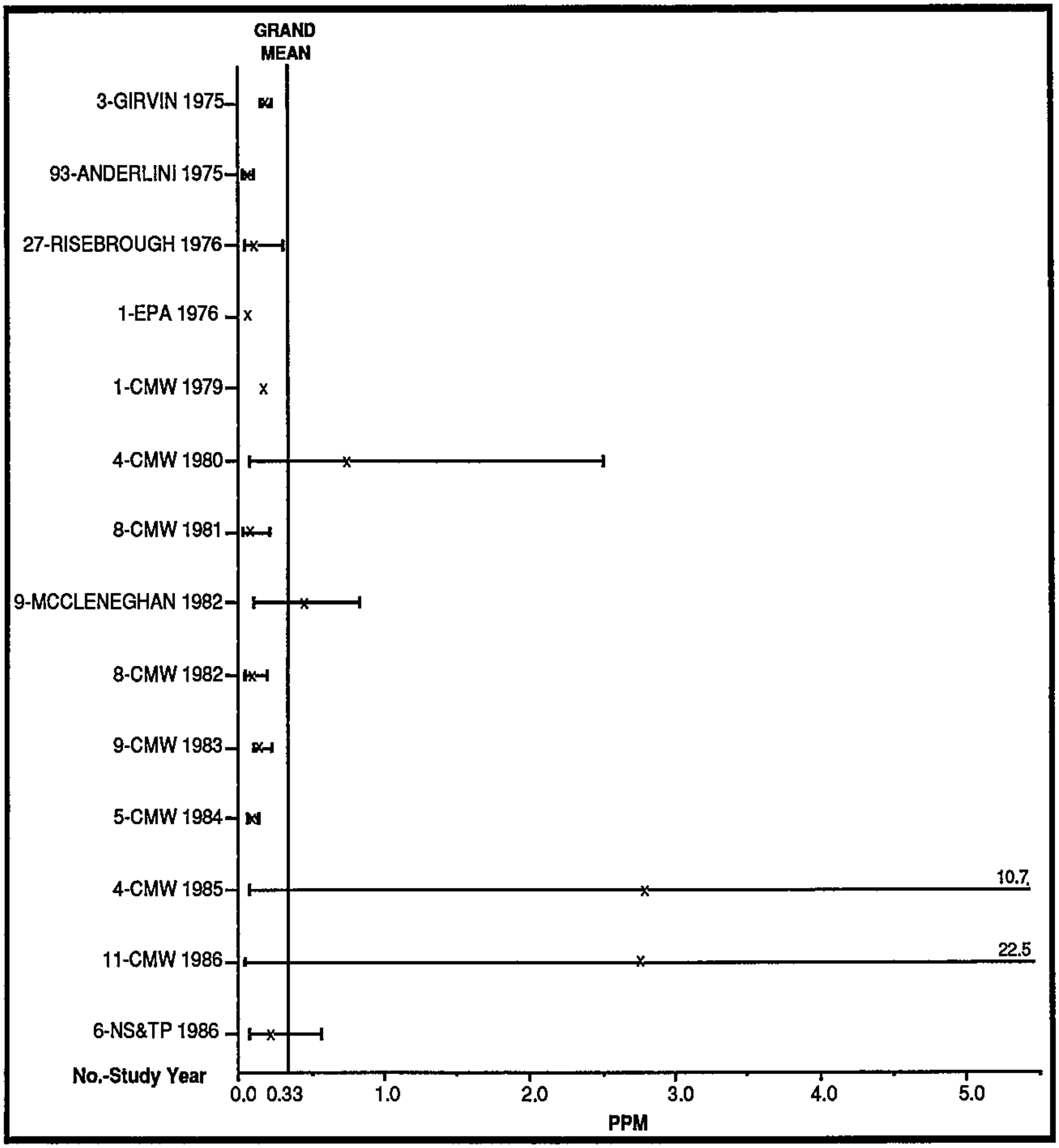


Figure 83. Mean concentration (ppm dw) of tDDT in mussels (Mytilus edulis or M. californianus) by study and year (No.=number of samples, bars represent the range).

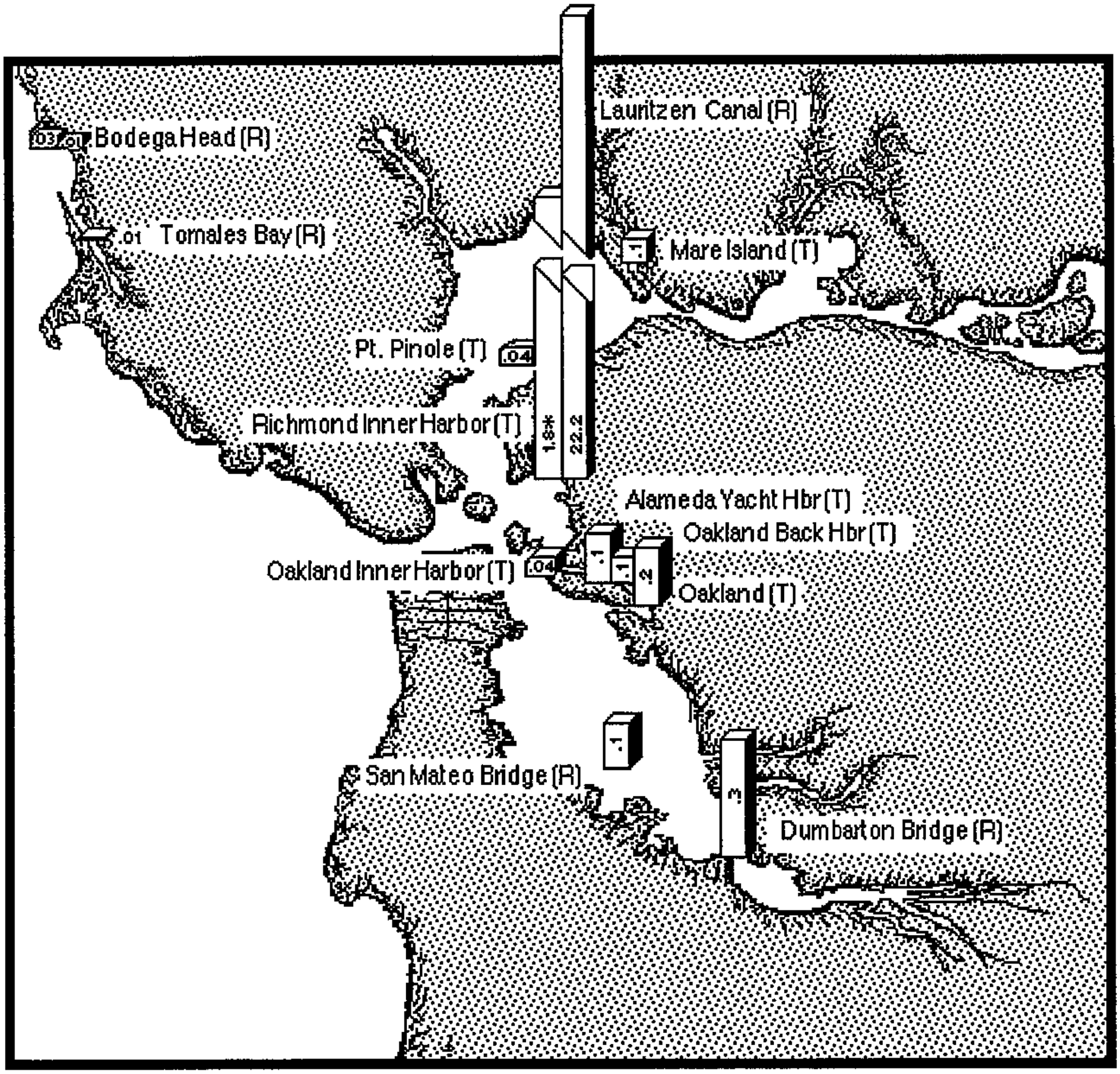


Figure 84. Total DDT (ppm dw) in mussels, 1985-86. Data from NS&T Program (Boehm et al., 1987) and California State Mussel Watch (Hayes and Phillips, 1987). R indicates resident mussels (M. edulis), T indicates transplanted mussels (M. californianus). Data on transplanted mussels from four sites in the Santa Fe Channel and Richmond Inner Harbor were combined to produce a mean value for Richmond Inner Harbor.

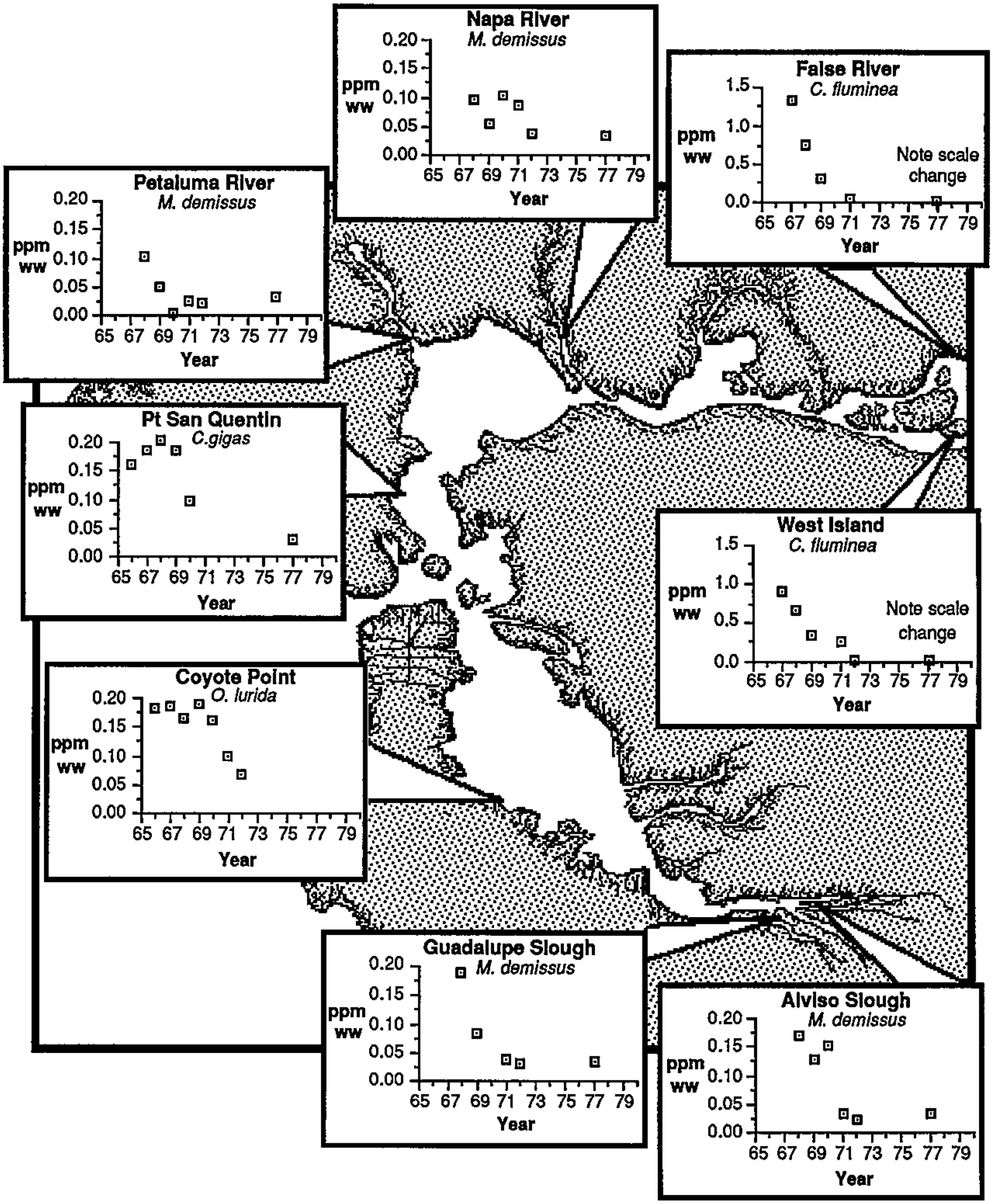


Figure 85. Temporal trends in tDDT concentrations (ppm ww) in clams, mussels, or oysters. From National Pesticide Monitoring Program data (Butler, 1973; Butler et al., 1978).

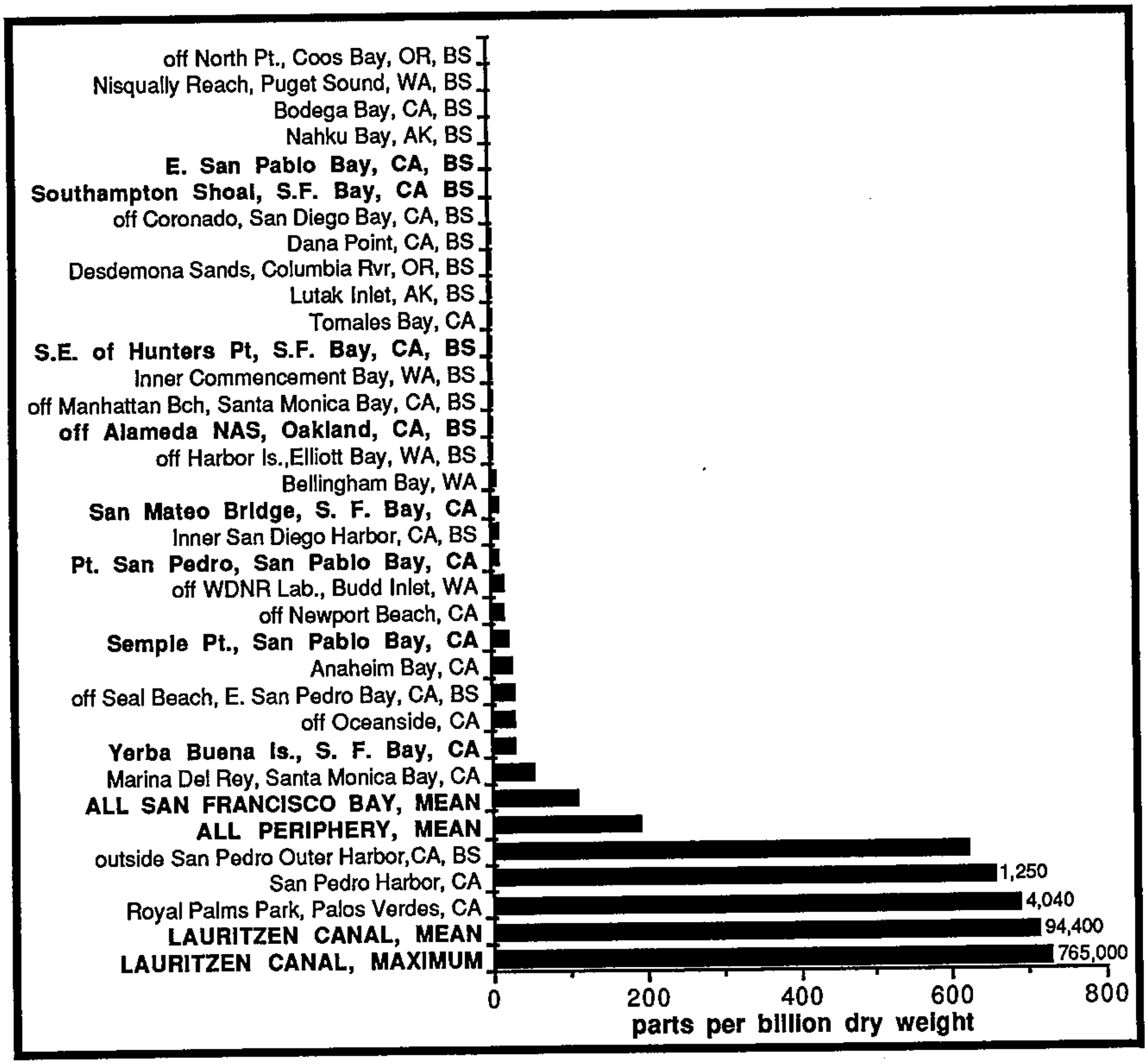


Figure 86. Comparison of tDDT concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Table 30), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name) .

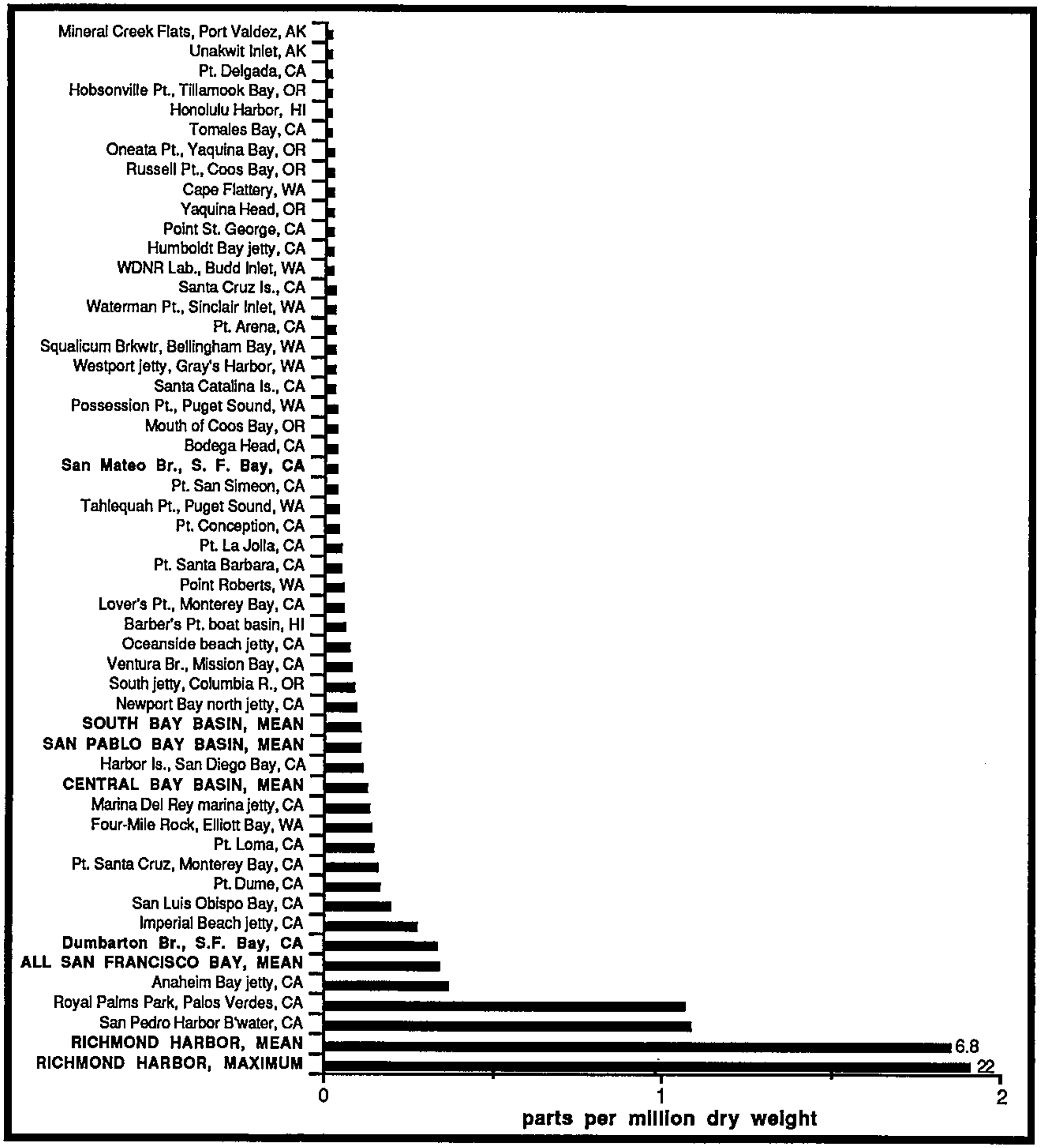


Figure 87. Mean tDDT concentrations in resident mussels (*Mytilus edulis*, *M. californianus*) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1972-1986) data for San Francisco Bay (from Table 32). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

11

GEOGRAPHIC AND TEMPORAL TRENDS IN PCB CONTAMINATION

A. Sediments

Since 1971, San Francisco Bay sediments have been intermittently analyzed for polychlorinated biphenyl (PCB) contamination. The concentrations of PCBs have been reported variously as: total PCBs (tPCBs); Aroclor 1254; Aroclor 1254 plus other PCBs; Aroclor 1254 and 1260; Aroclor 1242, 1254, and 1260; and the sum of eight levels of chlorination of the biphenyls (dichlorobiphenyl through nonachlorobiphenyl) (Table 35). Because of these differences in the manner in which PCBs have been analyzed and reported, it is difficult to compare data from different data sets. This report summarizes the data generated by either of two methods: those which involved totaling three Aroclors and those which involved totaling eight individual chlorinated biphenyls. Among the data sets available for PCBs in the Bay, those based upon these two methods are most likely to be comparable. Based on the 1984-86 data of NOAA's NS&T Program (Boehm et al., 1987; Chapman et al., 1986; NOAA, 1987a), which measured the concentration of eight individual chlorinated biphenyls, and Spies et al. (1985a) and Spies (1987, personal communication), who measured the concentrations of the three Aroclors (1242, 1254, and 1260), the mean concentration of PCBs in San Francisco Bay sediments for 1984 and 1986 was 99 ppb (Table 34) with a standard deviation of 159 ppb. The median concentration for those three years was 46 ppb, and the range was 5 to 824 ppb. These numbers are based on the data from 64 samples.

(1) Geographic Trends

Table 34 compares the summary statistics for tPCB concentrations in the basins with those for the peripheral areas of the Bay based on data from NOAA's NS&T Program, Spies et al. (1985a), and Spies (1987, personal communication) for 1984-86. Both the mean and median tPCB concentrations of the periphery are approximately seven times greater than those of the open basin areas. While this large difference between PCB concentrations in the basins and the peripheral areas appears to be clearly significant even when statistically analyzed with a one-tailed T-test (α=0.01), there are two main reasons why any conclusions must be drawn with caution. Spies' laboratory generated 80 percent of the peripheral data and only 20 percent of the basin data, and while the methods of Spies' laboratory and NOAA's NS&T Program are considered to be comparable, they are not identical. Some of the difference between the basin and periphery means may be due to differences in sampling or analytical techniques. Also, 80 percent of the peripheral samples were taken in 1986, while only 60 percent of the basin samples were taken in that year, and the difference between basins and periphery might partially reflect a temporal difference as opposed to a geographic trend.

Figure 77 displays this difference between the basin and peripheral sites. The highest mean concentration of tPCBs (636 ppb) was found in India Basin, while the highest concentration at a basin site was 94 ppb in samples collected off Yerba Buena Island, which had a mean tPCB concentration of less than one-sixth that of India Basin. The India Basin mean was based on two samples, while the Yerba Buena Island mean was based on three samples. The highest single-sample value for tPCBs was 824 ppb; it was measured in a sample taken a quarter-mile down the Alameda Estuary from the 29th Avenue Bridge. Other areas of high PCB contamination were Islais Creek, China Basin, and Oakland Middle and Inner Harbors. In Islais Creek, Spies (1987, personal communication) analyzed a single sample with a concentration of 445 ppb, while Chapman et al. (1986) analyzed three samples with concentrations ranging from 57 to 255 ppb and having a mean of 164 ppb. The areas showing the lowest levels of tPCB contamination in the Bay were the NS&T Program Benthic Surveillance Project sites at Southhampton Shoal and in eastern San Pablo Bay (11 and 14 ppb, respectively). Chapman's site in western San Pablo Bay had a mean value (based on three samples) of 11 ppb in 1985, but in 1986, the NS&T Program Mussel Watch site and Spies' site in the same general area of San Pablo Bay had mean values of 33 and 56 ppb, respectively.

The NS&T Program Benthic Surveillance and Mussel Watch projects analyzed for tPCBs in samples from Bodega Bay and Tomales Bay, respectively. The Bodega Bay site had a mean tPCB concentration of 5 ppb, while the Tomales Bay site had a mean of 4 ppb. When compared to these two reference sites, the mean concentrations per site in San Francisco Bay sediments range from approximately 2 to 100 times more contaminated.

When the data from Spies' studies were analyzed statistically, none of the sites was significantly different (p=0.05). However, when the NS&T Program data were subjected to the same statistical analysis, the five sites with the highest means (Islais Creek, off Yerba Buena Island, San Mateo Bridge, off Hunters Point, and off Oakland) were significantly different than the three San Francisco Bay sites with the lowest means (east San Pablo Bay, Southhampton Shoal, and west San Pablo Bay) as well as the two reference sites (Bodega and Tomales Bays) (Figure 89). The two sites with moderate means (Point San Pedro and Semple Point) were not significantly different than any of the other sites including the reference sites. When all the data from the NS&T Program basin sites were pooled (37 ppb) and compared to the single peripheral site (Islais Creek, 164 ppb), the peripheral site was significantly different than the pooled basin sites, based on a one-tailed T-test (α=0.01). In addition, the NS&T Program data suggest that San Pablo Bay has less PCB contamination than central or south bays since four of the five Bay sites with the lowest means were in San Pablo Bay; the fifth site was Southampton Shoal.

Additional studies of PCB contamination of San Francisco Bay included dredging studies conducted under the auspices of the COE in 1971 and 1972; and the COE's Dredge Disposal Study in 1973. Between 1971 and 1972, six harbor and channel areas were sampled for Aroclor 1254 and/or 1260. While the absolute concentration values cannot be compared to the data of NS&T Program and Spies because only some PCBs were measured, the relative concentrations between COE sampling areas are of interest. The highest mean concentrations of Aroclor 1254 were found at Hunters Point (126 ppb) and Alameda NAS (125 ppb), while the lowest mean concentrations were found in Mare Island Strait (17 ppb) and Redwood City Harbor (17 ppb). Intermediate mean concentrations were found at Point Molate (81 ppb) and in Richmond Harbor (42 ppb). Mare Island Strait and Redwood City Harbor were found to be significantly different than the three most contaminated areas (Hunters Point, Alameda NAS, and Point Molate) (p=0.05).

In 1973, as part of the COE's Dredge Disposal Study, Serne and Mercer (1975) analyzed ten samples from eight areas for undefined PCB's (Table 35). The highest PCB concentration was found in the Oakland Inner Harbor Reach (833 ppb); the second highest concentration was at Islais Creek Shoal off the mouth of Islais Creek (280). The lowest concentration of PCBs was 26 ppb in Pinole Shoal Channel, followed by 30 ppb in Southhampton Shoal Channel, and 84 ppb in Mare Island Strait.

In 1979, CH^2M-Hill analyzed samples from 23 sites along the west side of south Bay for Aroclor 1254 (Table 35). All but two of the sites had mean concentrations of 20 ppb or less. The two sites with the highest concentrations of Aroclor 1254 were at the head of Islais Creek channel (500 ppb) and at the head of the China Basin channel (28 ppb). Four sites had concentrations below the detection limit of 5 ppb (two in Brisbane Lagoon, one off Sunnydale, and one between Sunnydale and Brisbane Lagoon).

ANATEC analyzed 62 samples from nine areas for undefined PCBs from 1980 through 1981 (Table 35) (Kinney and Smith, 1982). The three areas with the highest mean concentration of PCBs were off Virgina Street in Berkeley (216 ppb), in San Leandro Bay (215 ppb), and in San Leandro Creek (173 ppb). The areas off Virginia Street and in San Leandro Creek were found to be significantly different than the five areas with the lowest concentrations of PCBs (p=0.05): Berkeley Marina (43 ppb), off the Stege Plant (40 ppb), off Alameda (30 ppb), off Point Isabel (27 ppb), and Berkeley Flats (16 ppb). San Leandro Bay was not significantly different than any of the other areas mainy because of the wide range of individual sample concentrations: 5 ppb (one of the lowest values) to 700 ppb (the highest single sample value),

In addition to his work in 1986, Spies analyzed 11 samples from four sites in 1984 for Aroclor 1254 and 1260 (Spies et al., 1985b). The four sites had means ranging from 5 ppb off Alameda to 30 ppb in San Pablo Bay.

As part of the homeporting study for the *U.S.S. Missouri,* the U. S. Navy in 1986 and ESA in 1987 analyzed a total of 20 samples for PCB contamination at Hunters Point Naval Shipyard and Treasure Island.

All samples were reported as being below detection limits; the detection limits ranged from 6 to 880 ppb in individual samples.

In 1986, the U. S. EPA analyzed 10 sediment samples from around south Bay for tPCBs in the form of Aroclor 1254. Figure 78 displays the results of these analyses. Each of the values in Figure 78 is based on unreplicated analyses except for the site with 24 ppb toward the southern end of south Bay; it is the average of two replicate samples (14 and 34 ppb). Based on these data, Aroclor 1254 concentrations in south Bay sediments vary only by a factor of 2.

(2) Temporal Trends

Because of the intermittent nature of data collection and the varied categories of PCBs analyzed, it is difficult to determine whether any long-term trends, either of increasing or decreasing concentrations, exist with regard to PCB concentrations in San Francisco Bay sediments. Table 35 gives the means, standard deviations, and ranges of the data located for use in this chapter, broken down by year and source. In addition, it shows the manner in which PCB concentrations were reported. It was unclear regarding which PCB compounds were actually measured for the category "PCBs (undefined)." The variation between years and data sources reflects more the variation in sites sampled (basin vs periphery) and the specific PCBs measured than any yearly changes. The highest mean concentration, 200 ppb, was for Spies' 1986 data set; this data set includes values from several highly contaminated peripheral areas and is based on the total concentration of all three Aroclor compounds. The lowest mean concentration, 17 ppb, was from Spies' 1984 data set and the 1986 EPA data set. With one exception, all the sites sampled for the latter data set were located in open areas of the south Bay basin and only Aroclor 1254 was measured.

Figure 79 shows the mean concentrations of tPCBs at six sites for which data were available for more than one year and were analyzed by the same methods (summation of eight chlorination levels). The only site which showed a significant difference (α=0.01) between years, based on a one-tailed T-test, was the Oakland site, which had a PCB concentration of 61 ppb in 1984 and 30 ppb in 1985. However, no conclusions concerning the existence of temporal trends can be drawn based on this data due to the short time period involved.

B. Biota

PCB concentrations have been determined in biota of San Francisco Bay by 19 surveys since 1972 (Table 2).

Fish caught from San Francisco Bay have yielded a total of 402 samples of flesh, liver, gonad, or other tissue for PCB analyses. The species sampled most frequently for PCB analyses has been striped bass (*Morone saxatilis*) (258 samples), followed by starry flounder (*Platichthys stellatus*) (110 samples). Highest concentrations of PCBs in fish have been detected in samples of striped bass (Whipple et al., 1984, 1987). Concentrations of PCBs in striped bass liver have reached a maximum 19.0 ppm ww in a fish caught off Tiburon in 1980. Levels of PCBs in flesh and gonads have been highest in fish from the Sacramento River in 1980 (4.0 and 10.74 ppm ww respectively). Mean concentrations of PCBs in striped bass have ranged from 0.47 ppm ww in flesh to 2.13 ppm in gonads. Most sampling has occurred in the Sacramento-San Joaquin River Delta, although a few samples have been taken from off Tiburon and as far up the Sacramento River as Clarksburg.

Based upon all the data on PCB concentrations in mussels (*Mytilus edulis, M. californianus*) sampled from 1975 through 1986 in the San Francisco Bay system (193 samples), the grand mean concentration in PCBs has been 0.65 ppm. Because of high detection limits for some surveys (up to .5 ppm) and the fact that many surveys reported PCB levels only by ww, this mean is an estimate. The grand mean PCB concentration in mussels exceeds the overall means for Tomales Bay and Bodega Head by a factor of 13. The means and ranges in PCB concentrations in mussels are summarized for individual studies and compared to the grand mean for the Bay in Figure 88.

(1) Geographic Trends

The sampling of clams (*Tapes semidecussata* or *Mya arenaria*) from 15 sites in San Francisco Bay in 1972 by Shimmin and Tunzi (1974) showed highest concentrations of PCBs to have occurred at Point Richmond (0.25 ppm ww, approximately 2.2 ppm). All the other sites had clams with lower concentrations of PCBs (between 0.1 and 0.12 ppm ww, approximately 0.1 to 1.0 ppm dw).

Anderlini et al. (1975b) analyzed 93 samples of transplanted bay mussels (*M. edulis*) at a spoil disposal site in central Bay and a site near the EBMUD outfall in south Bay. They reported a mean concentration of PCBs of 0.53 ppm and a range of 0.21 to 1.3 ppm (Figure 92). The highest concentrations (0.84 to 1.3 ppm) were found in samples from EBMUD sites 1 and 2 located nearest the outfall.

In 1976, resident mussels (*Mytilus edulis*) from 27 sites around the bay were sampled by Risebrough (1978) (Figure 93). The mean concentration for the study was 0.60 ppm with a range of 0.25 to 1.5 ppm (Figure 92). Highest concentrations of PCBs were detected in mussels from Oyster Point (1.5 ppm) and Redwood City Harbor (1.3 ppm). Mussels from sites in the south Bay generally contained higher concentrations of PCBs than mussels from the central Bay, which generally contained higher concentrations of PCBs than mussels from San Pablo Bay.

A wide range in PCB concentrations was reported for samples of bay mussels (*Mytilus edulis*) collected from nine areas in the Bay by two surveys in 1980 (Figure 92) (McCleneghan et al., 1982; Hayes et al., 1985). Highest levels of PCBs were detected in mussels from peripheral and basin sites at Point Isabel near Richmond (2.5 to 4.6 ppm). Mussels from Coyote Point also contained high levels of PCBs (2.9 ppm). Samples analyzed by McCleneghan indicate that PCB concentrations at all sites were very high (Figure 92), especially those from Point Isabel, which were significantly higher than those at all other sites, except Coyote Point ($p=0.05$). PCB levels in mussels from Coyote Point were also significantly different than those from other sites (range = 1.1 to 1.7 ppm) ($p=0.05$).

Striped bass (*Morone saxatilis*) were sampled from six sites in the Bay system in 1980 by Whipple et al. (1984) (Figure 94). The highest concentrations of PCBs in liver and gonad were detected in fish collected off Tiburon (5.15 and 4.83 ppm ww). The highest concentrations in flesh were detected in fish from the Sacramento River at Clarksburg (0.75 ppm ww). Concentrations of PCBs in gonads of striped bass were not significantly different between sites ($p=0.01$). Levels in liver and flesh tissue were significantly different only between Tiburon and Clarksburg ($p=0.1$ for liver comparison, $p=0.05$ for flesh comparison). Mean concentrations in flesh were higher at Clarksburg (0.75 ppm ww) than at Tiburon (0.19 ppm ww), while in the livers, the mean concentrations were higher at Tiburon (5.15 ppm ww) than at Clarksburg (2.59 ppm ww).

Starry flounder (*Platichthys stellatus*) were sampled from five sites in San Francisco Bay in 1983 by Spies et al. (1985a). The highest concentrations of total PCBs in livers of females were detected in fish collected off Richmond (2.33 ppm ww) and off Berkeley (1.85 ppm ww). Fish taken in the Oakland Outer Harbor and San Pablo Bay contained lower PCB concentrations in liver (0.58 and 0.62 ppm ww, respectively). But, these differences were not statistically significant ($p=0.05$).

The NS&T Program (NOAA, 1987a) surveyed fish from four sites in San Francisco Bay and a site in Bodega Bay in 1984. The highest concentrations of tPCBs were detected in livers of starry flounder from a site off Hunters Point (6.99 ppm). Lowest concentrations were detected in starry flounder livers from eastern San Pablo Bay (1.19 ppm) and Bodega Bay (0.55 ppm). Concentrations of tPCBs in starry flounder liver were significantly lower at the San Pablo Bay site than for those at both the Hunters Point and Southhampton Shoal sites ($p=0.05$). In 1985, most of the sites were resampled. The highest concentrations (4.24 ppm) of tPCBs were again detected in fish collected off Hunters Point (this time in white croaker (*Genyonemus lineatus*) (Table 35). Again, the lowest levels of PCBs were detected in livers of fish from eastern San Pablo Bay (1.88 ppm in starry flounder) and Bodega Bay (0.51 ppm in white croaker and 1.28 ppm in starry flounder). PCB levels were significantly different between only Bodega Bay and Southhampton Shoal fish ($p = 0.05$).

Total PCB concentrations in both resident *Mytilus edulis* and transplanted *M. californianus* analyzed by EPA or the California Mussel Watch Program were generally below 1.0 ppm from 1976 through 1986 (Figure 92). However, some samples of *M. californianus* transplanted to sites off Hunters Point, Treasure Island, and the San Mateo and Dumbarton bridges in 1981 had 1.3 to 1.8 ppm tPCBs. These relatively high concentrations were not reported at those sites in subsequent years (Figure 92).

In 1985 and 1986, the California Mussel Watch Program surveyed PCBs in *Mytilus califorianus* transplanted to 11 sites in San Francisco Bay and in resident *M. californianus* from Bodega Head (Hayes and Phillips, 1987) (Figure 95). The highest concentrations of tPCBs were detected in mussels transplanted to Richmond Harbor (0.51 to 1.13 ppm). Moderate concentrations of tPCBs were detected in mussels transplanted to a site in Oakland Inner Harbor (0.7 ppm). The range in concentrations for the surveys in 1985 and 1986 were relatively high (Figure 92) because of the samples from these peripheral areas. The lowest concentrations of tPCBs were detected in mussels transplanted to Mare Island Strait and Point Pinole in San Pablo Bay (0.08 to 0.06 ppm, respectively). PCBs were not detected in resident mussels from Bodega Head (with a detection limit of 0.01 ppm).

In 1986, resident *Mytilus edulis* were sampled from the San Mateo Bridge, the Dumbarton Bridge, and Tomales Bay, and *M. californianus* was sampled at a site at Bodega Head by the NS&T Program (Figure 95). The highest mean concentration (n=3) of tPCBs was detected in mussels from the San Mateo Bridge (0.68 ppm). The lowest levels of tPCBs were detected in mussels from Tomales Bay (0.05 ppm). The mean for the two sites in the Bay was 0.60 ppm and the range was 0.24 to 1.4 ppm. Levels of PCBs in mussels from Tomales Bay were significantly different from those at all other sites sampled (p=0.01).

The sampling of mussels by the NS&T Program was conducted at sites that had been previously occupied by other surveys. Except for one site, the results of PCB analyses by the NS&T Program are generally comparable to those of other efforts. At the San Mateo Bridge, other investigators (Hayes et al., 1985; Risebrough et al., 1978) found *M. edulis* and *M. californianus* to contain a mean concentration of 0.49 ppm between 1976 and 1983, with a range of 0.14 to 1.3 ppm. The NS&T Program detected a mean of 0.68 ppm in *M. edulis* at this site. The Dumbarton Bridge has also been sampled by Hayes et al. (1985) and Risebrough et al. (1978). The results of analyses of both species of mussels showed a mean of 0.56 ppm between 1976 and 1983, with a range of 0.18 to 1.3 ppm. The NS&T Program detected a mean of 0.52 ppm in *M. edulis* from the same site. Sampling of *M. edulis* from Tomales Bay has been conducted by Butler et al. (1974) and Hayes et al. (1985). The mean concentration of tPCBs in *M .edulis* between 1977 and 1982 was 0.07, with a range of from less than 0.01 to less than 0.25 (the highest detected value was 0.08 ppm), and the NS&T Program detected a mean of 0.05 ppm in *M. edulis* from Tomales Bay. However, at Bodega Head, the sampling by past surveys indicates far lower concentrations in *M. californianus* than that found by the NS&T Program. Sampling between 1977 and 1985 by the California Mussel Watch Program (Hayes et al., 1985; Hayes and Phillips, 1987), the EPA Mussel Watch between 1976 and 1978 (Farrington et al., 1982) in 1971 resulted in analyses of 24 samples. The mean concentration of tPCBs in mussels from these analyses was 0.03 ppm, with a range of from less than 0.01 to 0.08 ppm. The NS&T Program detected 0.21 ppm in mussels from Bodega Head in 1986, more than twice the highest concentration previously reported.

(2) Temporal Trends

PCBs in resident mussels (*Mytilus spp.*) have been measured frequently between 1976 and 1986 by four survey programs at Bodega Head or Tomales Bay (Butler et al., 1978; Hayes et al., 1985; Hayes and Phillips, 1986, 1987; Farrington et al., 1978; Boehm et al., 1987). Sampling of mussels in Tomales Bay has shown no trend in PCB concentrations between 1977 and 1986 (range = <0.01 to 0.08 ppm). At Bodega Head, tPCB concentrations were variable (0.01 to 0.07 ppm) between 1976 and 1981, and then dropped below the detection limit of 0.01 ppm (Hayes et al., 1985). However, in 1986, the NS&T Program found 0.21 ppm tPCBs in mussels at Bodega Head. Differences between years were not statistically significant (p=0.05).

Striped bass (*Morone saxatilis*) liver and gonad have been analyzed in various surveys of fish from Suisun Bay or the San Joaquin Delta between 1977 and 1984. The concentrations of PCBs in striped bass were variable, but the highest concentrations were detected in 1981 (Whipple et al., 1984). Differences between years were not statistically significant (p=0.05).

Transplanted mussels (*M. californianus*) have been resurveyed by the California Mussel Watch Program at eight sites in the Bay since 1980. At all sites, highest levels of PCBs were detected in mussels collected in January, 1981 (Figure 96). Levels since 1981 have been up to 10 times lower than maxima detected in that year. The largest apparent decline since 1981 has been seen at Point Pinole, where concentrations declined from 0.69 ppm to 0.06 ppm by 1986.

The fish species sampled by the NS&T Program (NOAA, 1987a) apparently have not been sampled by any other survey. However, Spies et al. (1985 a, b) sampled starry flounder from sites a short distance away from the NS&T Program sites in San Pablo Bay and Southhampton Shoal in 1983 and 1984. Results of these efforts are comparable with results of the NS&T Program. In western San Pablo Bay, starry flounder liver contained 0.34 and 0.62 ppm ww tPCBs in 1983 and 1984, respectively. Results of sampling in eastern San Pablo Bay by the NS&T Program showed starry flounder liver to contain 0.50 and 0.73 ppm ww in 1984 and 1985, respectively. Spies et al. (1985a,b) sampled starry flounder in 1983 and 1984 from the Standard Oil pier in Richmond, a short distance from Southhampton Shoal. Livers of these fish contained 2.33 ppm ww PCBs, as compared to 1.23 and 1.42 ppm ww found at Southhampton Shoal by the NS&T Program in 1984 and 1985, respectively.

C. Summary

PCB concentrations in the surficial sediments of San Francisco Bay have been measured intermittently since 1971 by different methodologies. Based on the two methods thought to give the most complete representation of PCB concentrations (summation of the three Aroclor concentrations and the summation of eight chlorination levels (di- to nona-), the mean concentration of PCBs in San Francisco Bay sediments for 1984-86 was 99 ppb. The highest concentration of PCBs were found in the peripheral areas of the Bay, which had an overall mean seven times higher than that of the basins (287 vs 41 ppb). India Basin, Islais Creek, and Oakland Outer and Inner harbors were the most contaminated. The highest level for a single sample (824 ppb in the Alameda Estuary) exceeded the mean concentration at the Tomales Bay site by a factor of over 200. When compared to reference sites in Bodega and Tomales Bays, mean concentrations in San Francisco Bay sites are approximately 2 to 100 times higher.

The data further suggest that San Pablo Bay has lower concentrations of PCBs than central or south Bays with the exception of Southhampton Shoal. This observation is supported by the data of the COE and Serne and Mercer which, for the PCBs they measured, indicated that Mare Island Strait and Pinole Shoal Channel had lower PCB concentrations than areas sampled in central and south bays.

Because of the limited available data, long-term trends in sediment contamination cannot be determined. Data available from 1984-86 do not indicate significant year-to-year changes.

Among the limited number of clams sampled in the Bay, the PCB concentrations have been highest in the Richmond/Berkeley/Oakland peripheral areas of the eastern central Bay. They have also been relatively high in some samples from parts of south Bay and relatively low in San Pablo Bay. A similar pattern appears to have occurred among mussels sampled in the Bay. The highest concentration (4.60 ppm from Point Isabel in 1980) exceeded the concentrations in reference areas by a factor of 80. Concentrations of up to 2.9 ppm have been reported for sites in south Bay. Concentrations in San Pablo Bay typically have been relatively low. Among bottom fish sampled in the Bay, samples from the Berkeley/Richmond area of central Bay have also had relatively high concentrations, while those from San Pablo Bay have been low. Fish and bivalves from coastal reference sites have had considerably lower PCB concentrations than their counterparts in the Bay.

There was an apparent peak in PCB levels in mussels in 1981, followed by a gradual decline to the present at most sites. An order of magnitude decrease from 1981 to the present has been documented in mussels at some sites. Data for striped bass also suggest a peak in 1981, however, the data set is too small to warrant conclusions regarding temporal trends. Given the variability in analytical techniques, some of the apparent change in concentrations in mussels may be attributable to between-laboratory variability. Insufficient data exist to determine temporal trends in other biota.

Mean concentrations of PCBs in sediments sampled from 1972 to 1986 in San Francisco Bay are compared in Figure 97 with means of three samples each for NS&T Program sites sampled in 1984 and 1986 along the Pacific Coast. San Francisco Bay historical areas are in bold, upper-case print. The NS&T Program sites in the Bay are in lower-case print. Those from the 1984 Benthic Surveillance Project are designated by "BS;" those from the 1986 Mussel Watch have no such designation. NS&T Program sites located within the Bay are in bold lower-case print. The overall historical mean concentrations for the Bay and the peripheral areas ranked relatively high for PCBs. They were exceeded only by sites in southern California and a site in Elliott Bay near Seattle where PCBs have historically been problems. Among the NS&T Program sites, three in the Bay ranked in the top ten. The remaining sites and the two reference sites had low PCB levels.

The mean concentrations of PCBs in mussels (*Mytilus edulis, M. californianus*) collected in San Francisco Bay in 1975 through 1986 are compared in Figure 98 with means from three samples of mussels each from NS&T Program Pacific Coast sites sampled in 1986. The historical areas are listed in upper-case print and the NS&T Program Mussel Watch sites in lower-case print. The two NS&T Program sites located within the Bay are listed in bold print. Mean concentrations in the Bay overall and its major basins were elevated somewhat compared to the 1986 Pacific Coast sites. The values from the Point Isabel area, however, were very high, equivalent to or exceeding the mean for Harbor Island in San Diego Bay, California. The 1986 means from the two San Francisco Bay NS&T Program sites remained elevated, ranking third and eighth, relative to the other 1986 sites. The two reference areas, Tomales Bay and Bodega Head, ranked 46th and 16th, respectively.

Table 34. Means, standard deviations, medians, and ranges of tPCB concentrations (ppb dw) in the surficial sediments of San Francisco Bay for 1985-86 based on data from NOAA's NS&T Program (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986); and from Spies (1987 unpublished manuscript).

AREA	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES
TOTAL DATA SET	115	172	50	6-824	52
BASINS	45.	35	37	6-140	37
PERIPHERY	287	245	221	51-824	15

Table 35. Means, standard deviations, medians, and ranges of tPCB concentrations (ppb dw) and compounds analyzed for in the surficial sediments of San Francisco Bay from 1971 through 1987 based on all available data.

SOURCE	YEAR	MEAN	SD	MEDIAN	RANGE	NO. of SAMPLES	AROCLORS 1242	AROCLORS 1254	AROCLORS 1260	PCBs (undefined)	8 CHLORINATED BIPHENYLS
COE	1971	40	28	41	14 - 66	4		X			
COE	1972	98	117	70	0.01 - 430	53		X		X	
SERNE & MERCER	1973	197	240	99	26 - 830	10				X	
CH2M-HILL*	1979	30			2 - 500	23		X			
ANATEC	1980	102	125	40	5 - 700	53				X	
ANATEC	1981	102	80	100	10 - 200	9				X	
SPIES*	1984	17			5 - 30	4		X	X		
NOAA	1984	27	22	22	5 - 70	16					X
NOAA	1985	48	66	23	6 - 255	18					X
NOAA	1986	58	38	42	20 - 140	12					X
SPIES	1986	200	234	93	13 - 824	22	X	X	X		
EPA	1986	17	3	66	9 - 34	10		X			
US NAVY**	1986	101	172	4.5	3 - 440	9				X	
ESA**	1987	107	113	25	25 - 250	11				X	

* Based on site means only, range is range of site means.
**All values were below detection limits (6-880 ppm), half the detection limits were used for the calculations.

Table 36. Total PCBs in fish liver (ppm dw), 1984-85, based on NS&T Program data (NOAA, 1987a).

SITE/SPECIES	TOTAL PCBS 1984	1985
SAN PABLO BAY		
STARRY FLOUNDER	1.191	1.882
SOUTHHAMPTON SHOAL		
STARRY FLOUNDER	3.734	3.607
OAKLAND		
WHITE CROAKER	4.772	
HUNTERS POINT		
STARRY FLOUNDER	6.99	
WHITE CROAKER		4.237
BODEGA BAY		
STARRY FLOUNDER	0.548	1.276
WHITE CROAKER	0.287	0.508
ENGLISH SOLE		0.346

Table 37. Means, medians, and ranges in concentration of tPCBs in mussels (*Mytilus edulis* and *Mytilus californianus*) collected by many investigators during 1975-1986 in basins and peripheral areas of San Francisco Bay (ppm dw).

AREA/SITE	MEAN	SD	MEDIAN	RANGE	N
SUISUN BAY					
BASIN	0.29	-	-	-	1
SAN PABLO BAY					
BASIN	0.30	0.19	0.27	0.06-0.69	13
PERIPHERAL-MARE ISLAND STRAIT	0.09	0.02	-	0.08-0.10	2
CENTRAL BAY					
BASIN	0.56	0.54	0.44	0.20-4.59	86
PERIPHERAL-RICHMOND HARBOR	0.76	0.21	0.68	0.51-1.13	7
POINT ISABEL	4.08	0.06	-	4.04-4.13	2
ALL PERIPHERAL	1.50	1.48	0.73	0.51-4.13	9
SOUTH BAY					
BASIN	0.69	0.36	0.59	0.14-2.90	67
PERIPHERAL-ALAMEDA YACHT	0.60	-	-	-	1
OAKLAND INNER HARBOR	0.60	0.27	0.70	0.18-0.88	5
OAKLAND OUTER HARBOR	0.44	-	-	-	1
BAYSHORE LAGOON	1.60	0.10	-	1.53-1.68	2
REDWOOD CREEK	0.56	0.43	0.41	0.20-1.30	6
ALL PERIPHERAL	0.71	0.47	0.60	0.18-1.68	15
ALL SAN FRANCISCO BAY	0.65	0.60	0.52	0.06-4.60	193
TOMALES BAY	0.05	0.02	0.05	0.03-0.08	7
BODEGA HEAD	0.05	0.06	0.02	0.02-0.24	30

ppb dw	Site Name	Study	No.
29	Semple Point	MW	3
12	San Pablo Bay	BS	6
56	San Pablo Bay	SP	3
33	Point San Pedro	MW	3
11	San Pablo Bay	T	3
51	Richmond	SP	2
12	Southampton Shoal	BS	6
58	Berkeley	SP	4
94	Yerba Buena Island	MW	3
85	Treasure Island	SP	1
129	Oakland Outer Hbr	SP	3
274	Oakland Middle Hbr	SP	1
194	China Basin	SP	1
45	Oakland	BS&T	6
398	Alameda Estuary	SP	3
445	Islais Creek	SP	1
164	Islais Creek	T	3
636	India Basin	SP	2
51	Hunters Point	SP	1
47	Hunters Point	T	3
75	San Mateo Bridge	MW	3

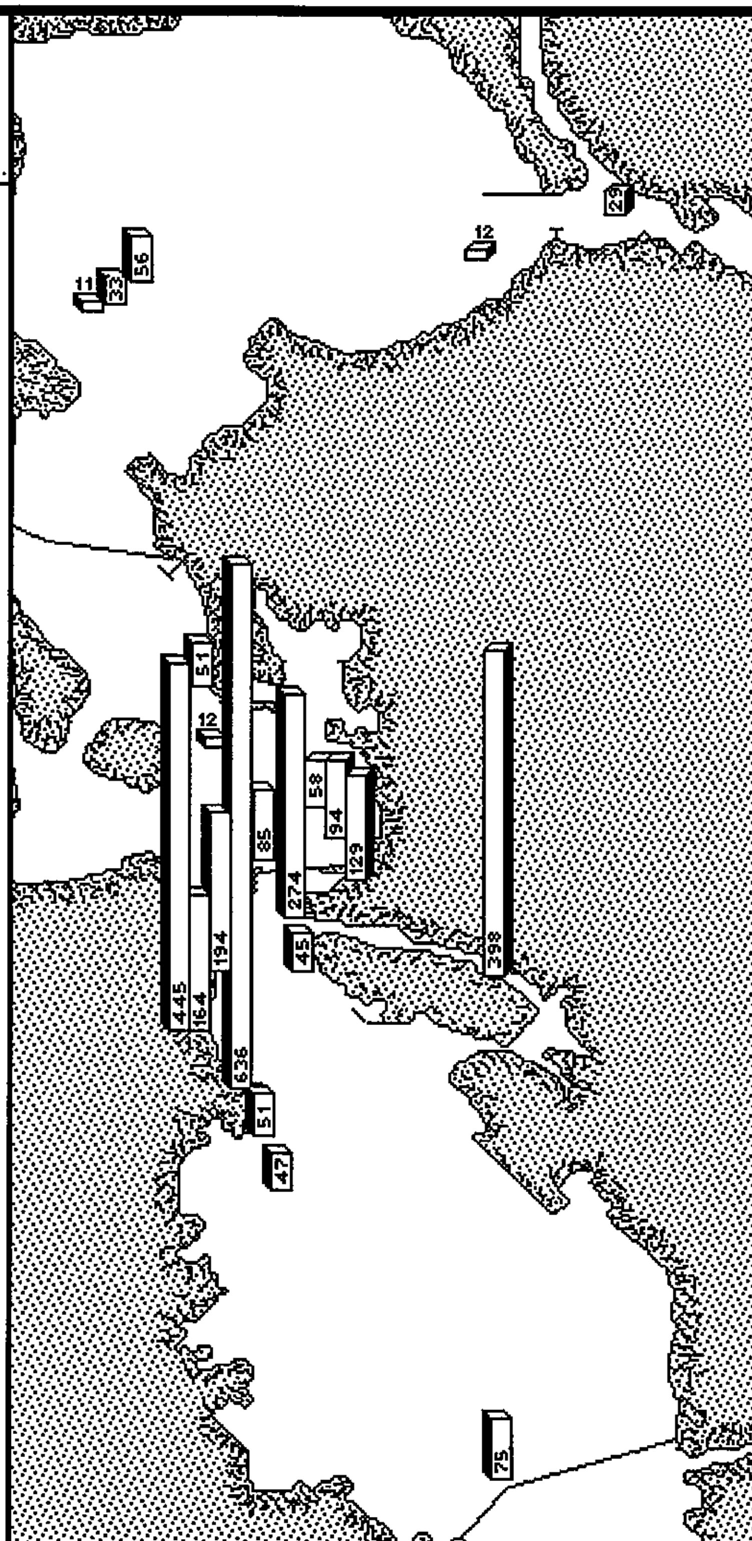


Figure 88. Mean PCB concentrations in the surficial sediments of San Francisco Bay for 1984-86 based on data from NOAA's NS&T Program and Spies, 1987 personal communication (ppb dw) (BS=Benthic Surveillance, MW=Mussel Watch, T=Sediment Quality Triad, SP=Spies) (NOAA analyzed for eight chlorination levels, Spies analyzed for Aroclor 1242,1254, and 1260).

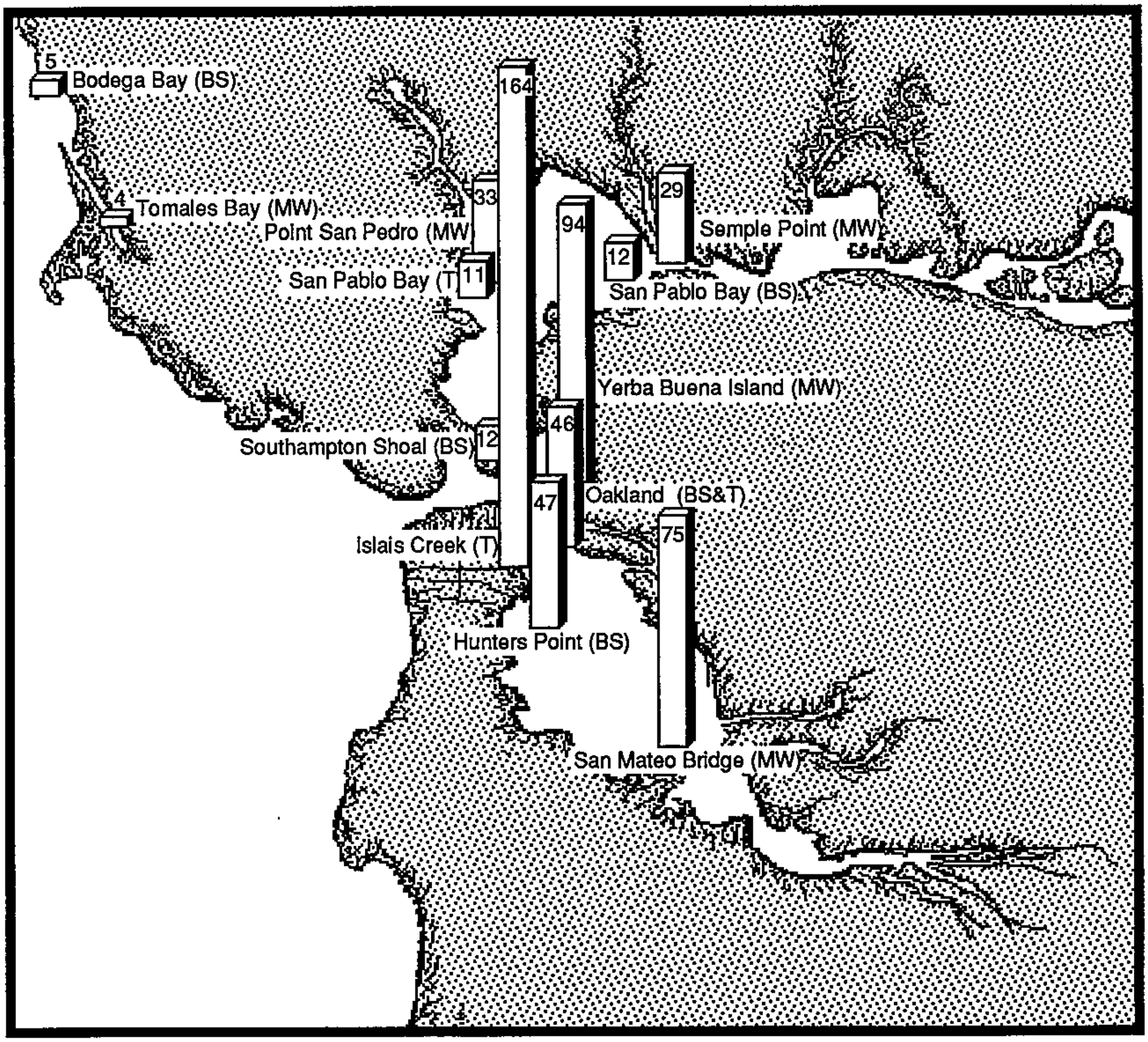


Figure 89. Mean tPCB concentrations (ppb dw) in the surficial sediments of NOAA's NS&T Program sites for the years 1984-86 (BS=Benthic Surveillance, T=Sediment Quality Triad, MW=Mussel Watch) (NOAA, 1987a; Chapman et al., 1986; Boehm et al., 1987).

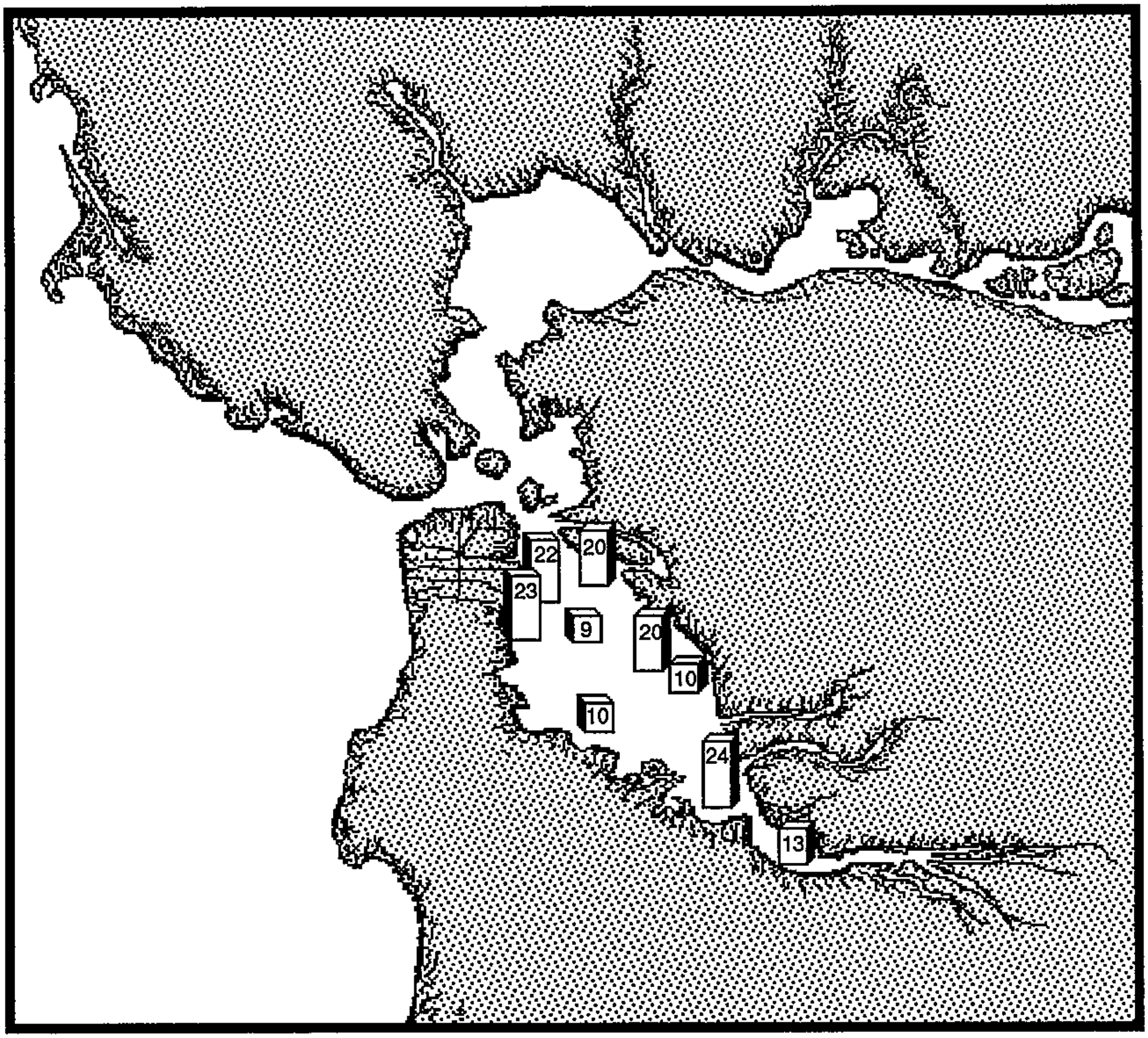


Figure 90. Mean tPCB concentrations (ppb dw) in the surficial sediments of south San Francisco Bay for 1986 based on EPA analyses for Aroclor 1254 (Baumgartner et al., unpublished manuscript).

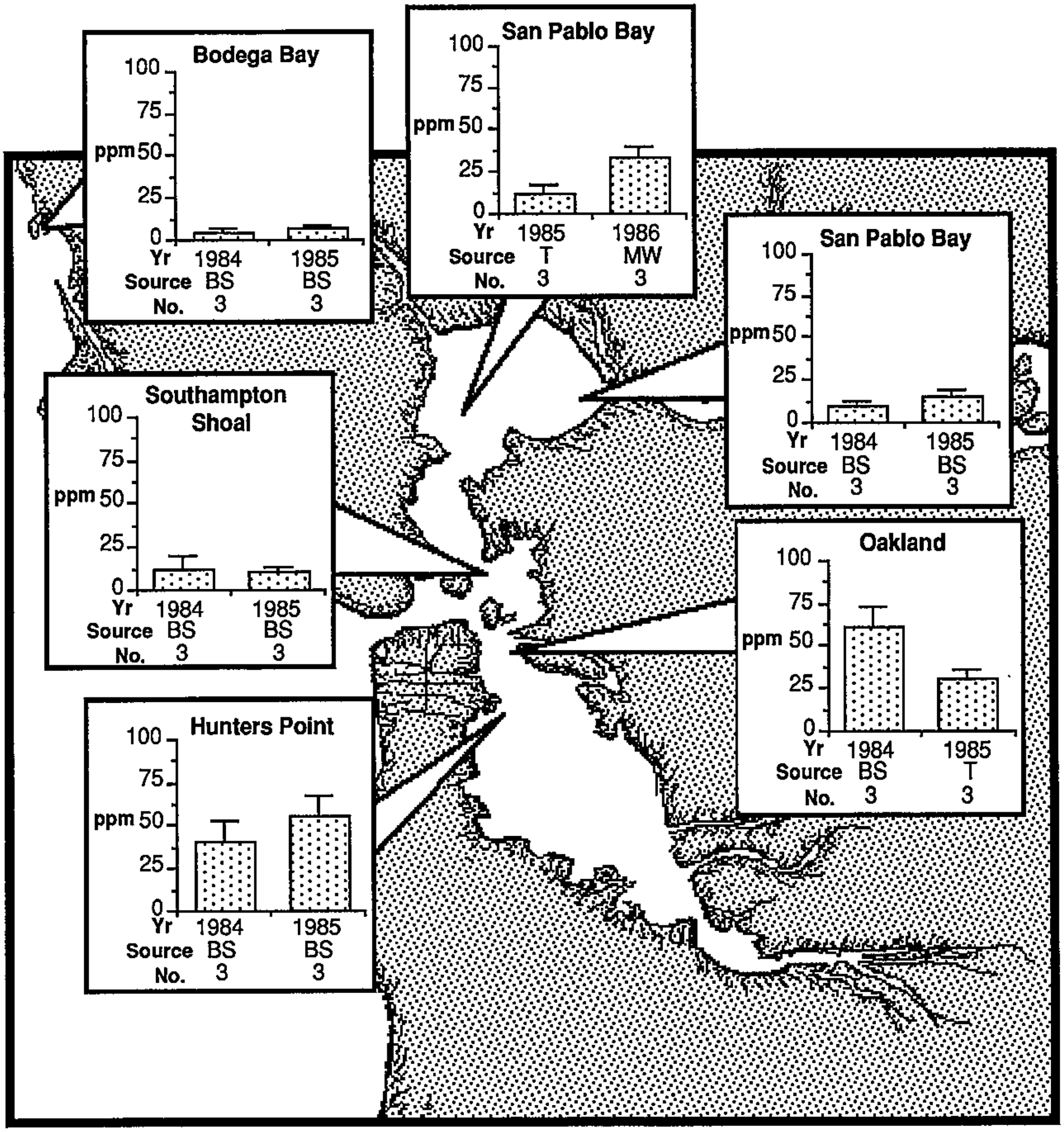


Figure 91. Mean PCB concentrations (ppb dw) in surficial sediments, with standard deviations, at six sites where data were available for more than 1 year from NOAA NS&T Program (BS=Benthic Surveillance, MW=Mussel Watch, T=Sediment Quality Triad) (NOAA, 1987a; Boehm et al., 1987; Chapman et al., 1986).

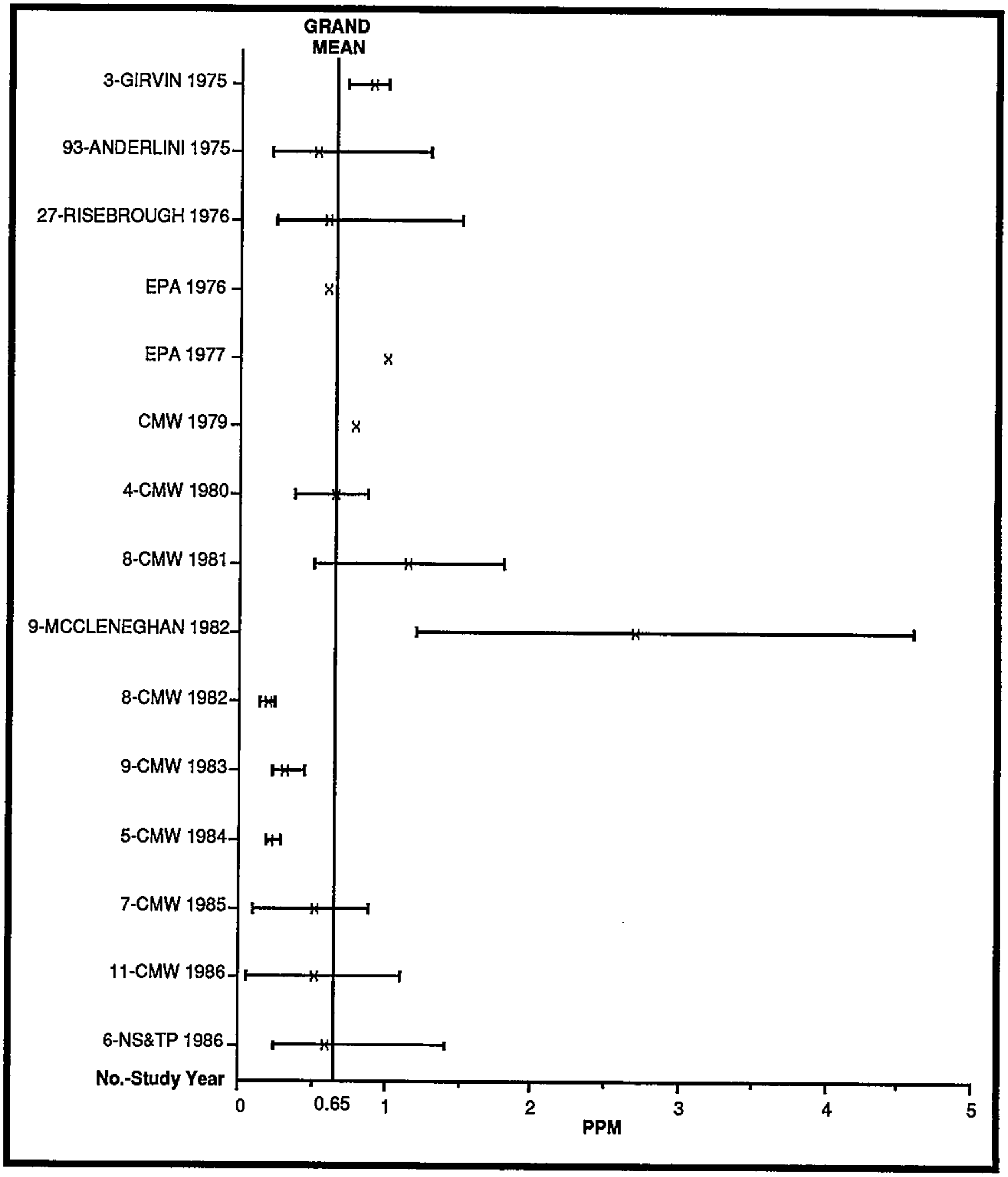


Figure 92. Mean concentration (ppm dw) of tPCBs in mussels (Mytilus edulis, M. californianus) by study and year (No.=number of samples, bars represent the range).

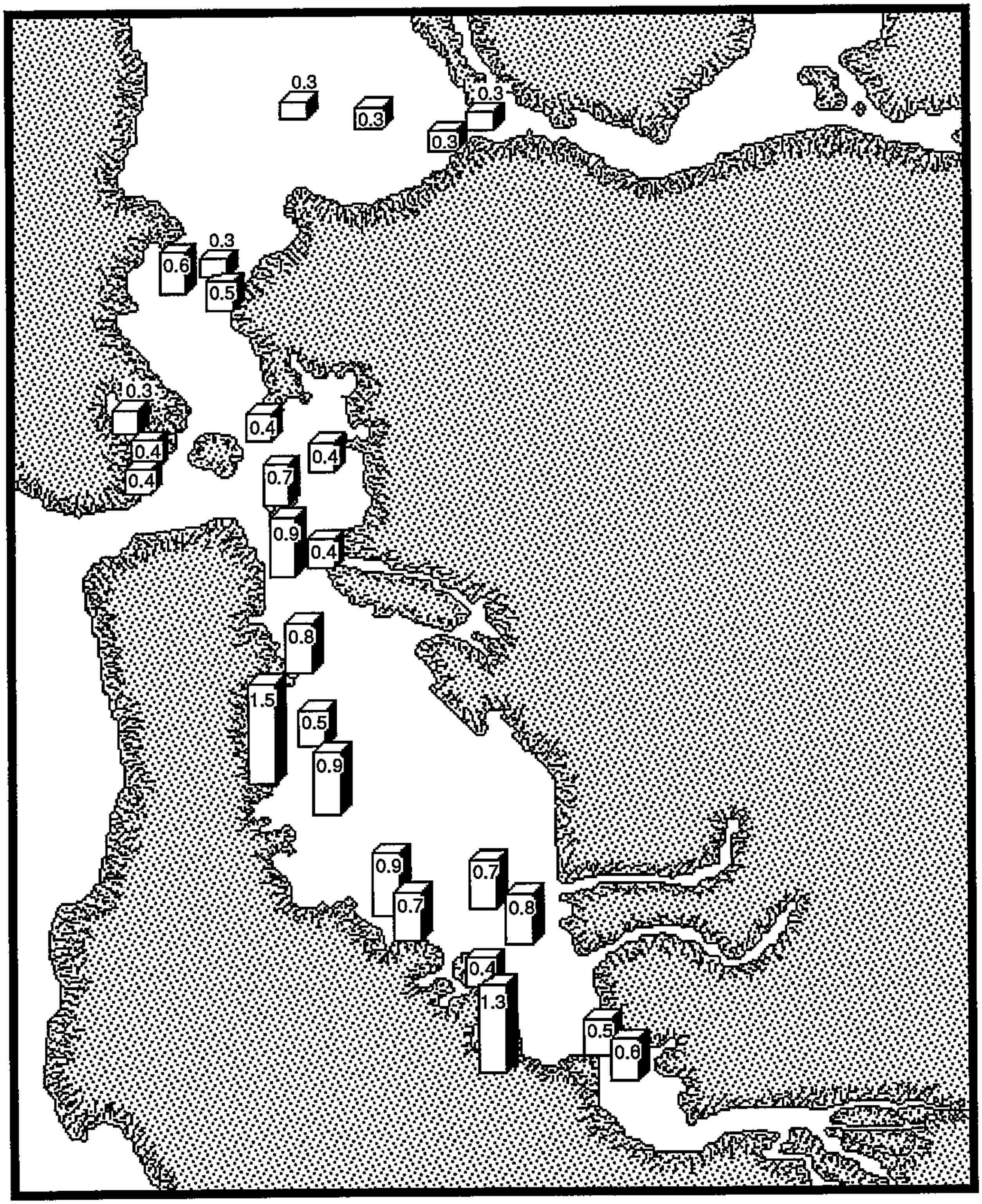


Figure 93. PCB 1254 concentrations (ppm dw) in bay mussels (Mytilus edulis), sampled during April 1976 (Risebrough et al., 1978).

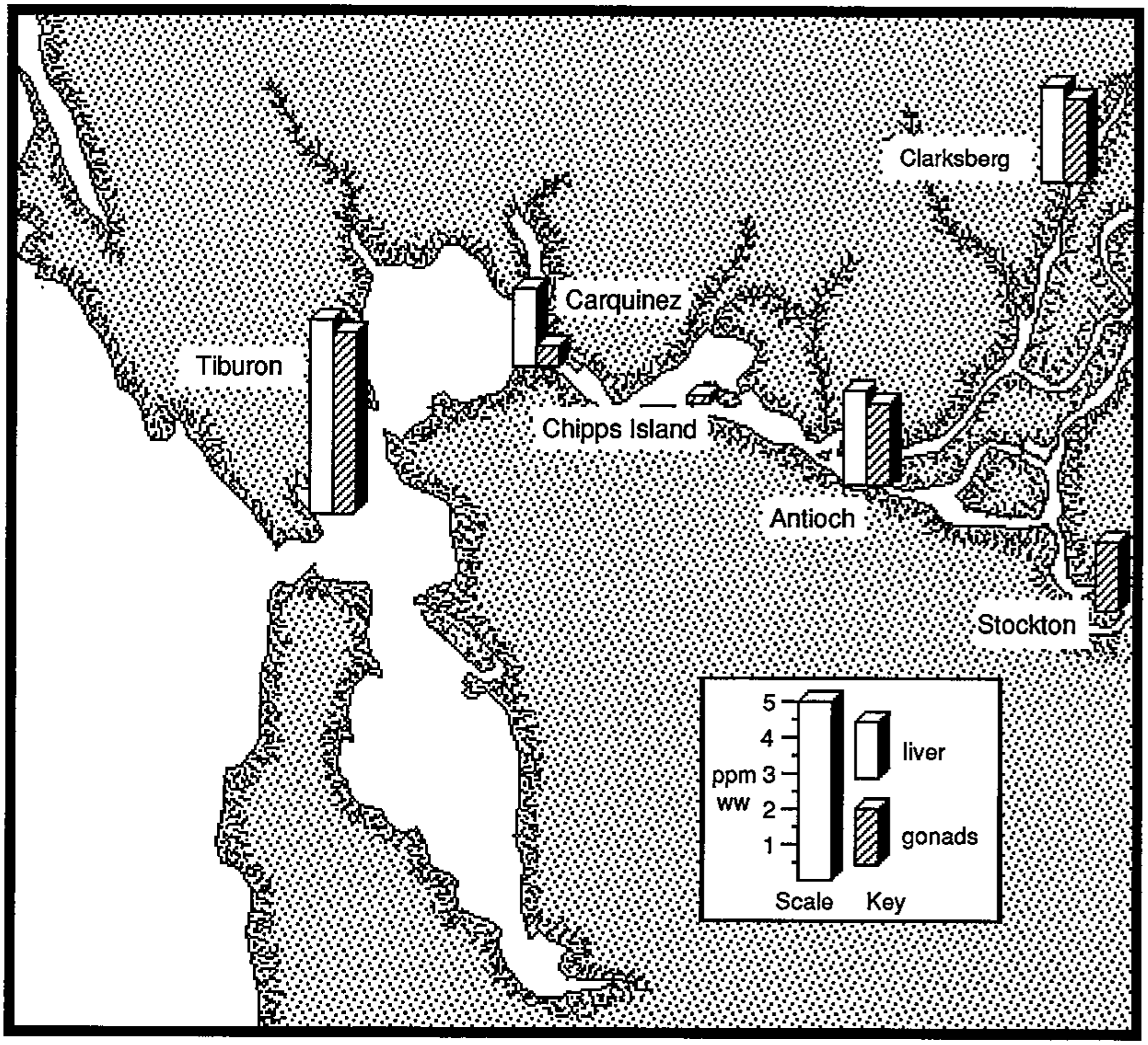


Figure 94. Total PCBs (ppm ww) in striped bass (Morone saxatilis) sampled during 1980 (Whipple et al., 1984).

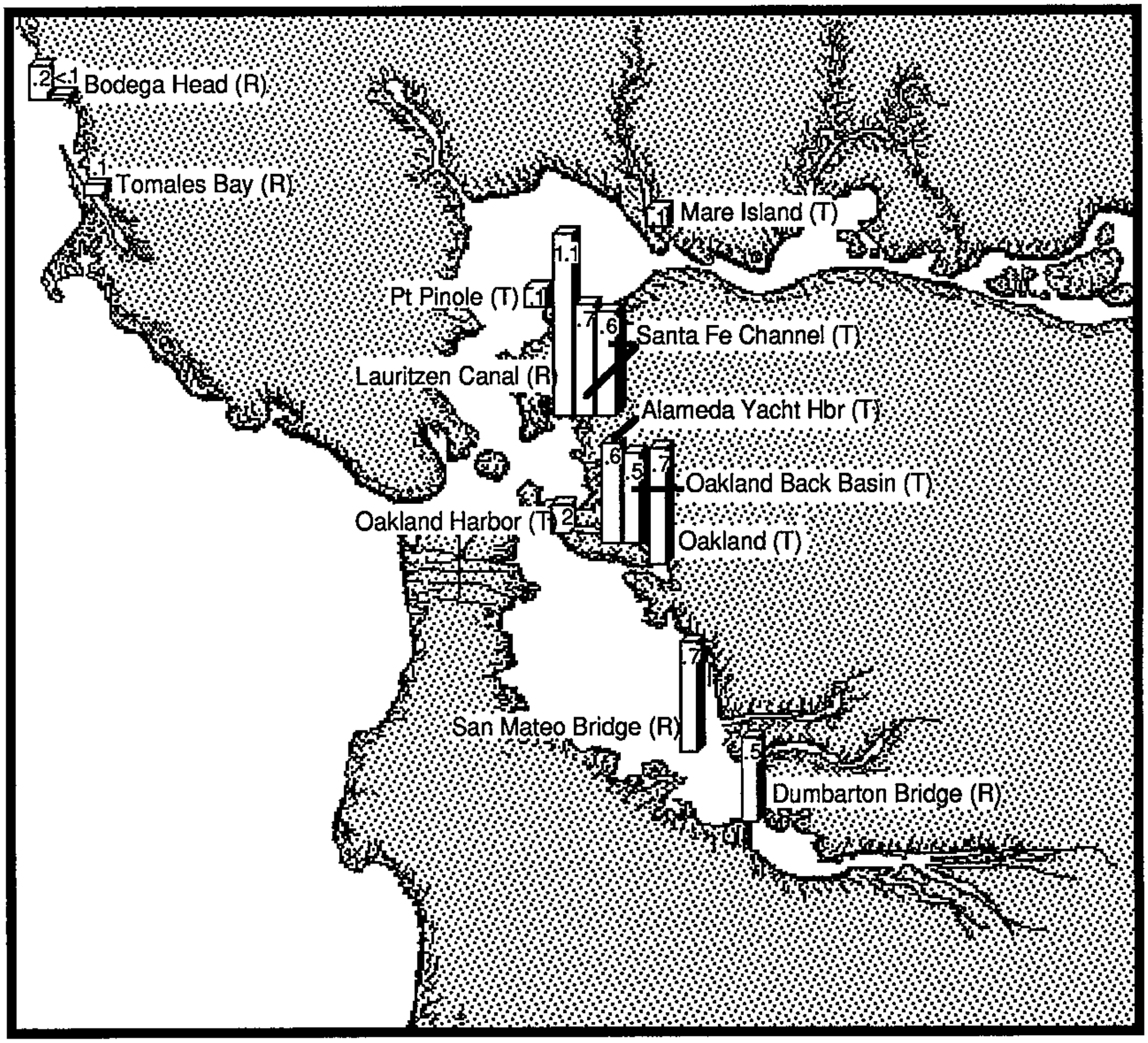


Figure 95. Total PCBs (ppm dw) in mussels for 1985-86, from NS&T Program and California Mussel Watch Program data (T indicates transplanted coastal mussels (Mytilus californianus), R indicates resident M. edulis, M. californianus) (Boehm et al., 1987; Hayes and Phillips, 1987)

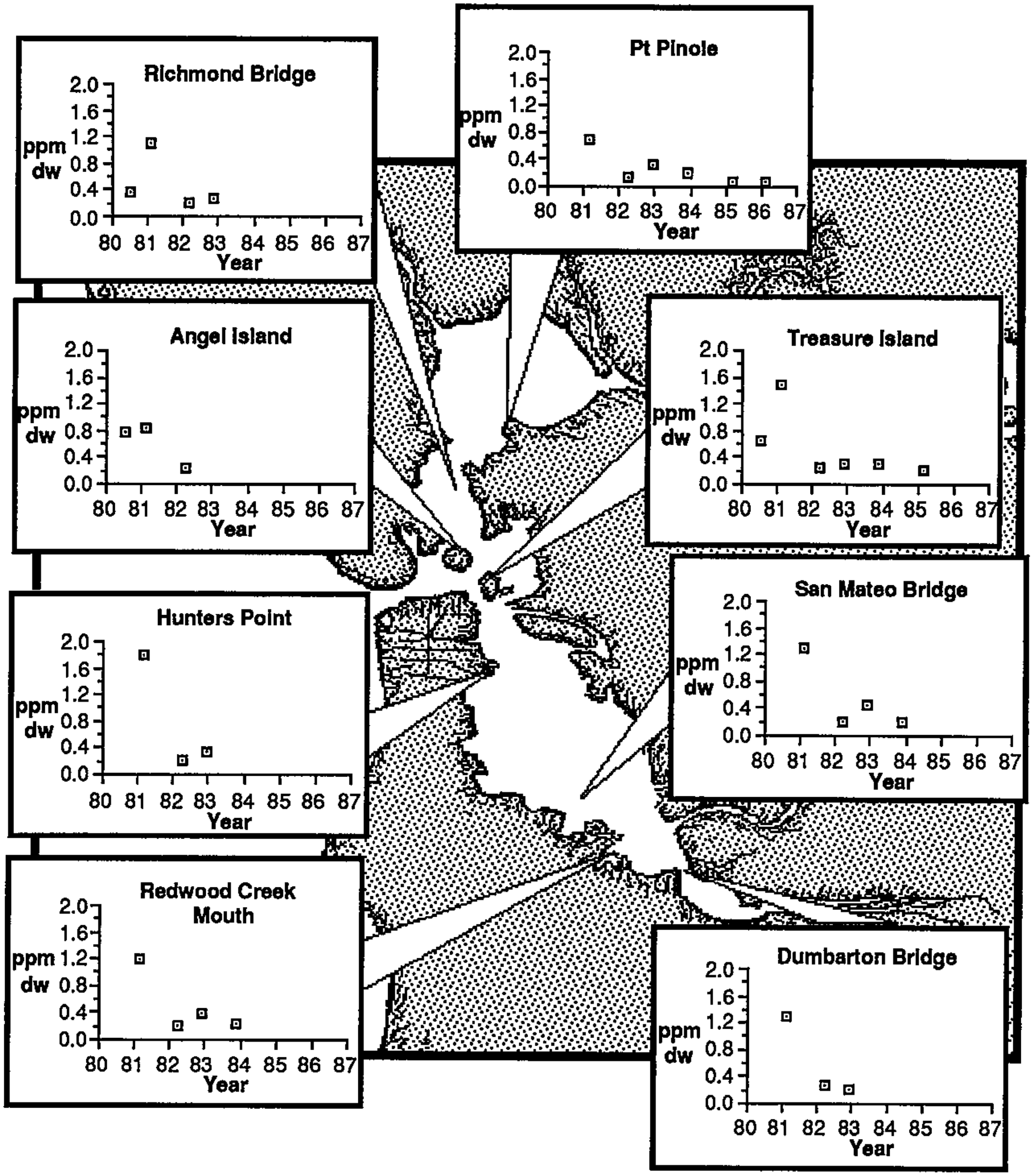


Figure 96. Temporal trends in total PCBs (ppm dw) in transplanted mussels (Mytilus californianus) from California Mussel Watch Program data (Hayes et al, 1985; Hayes and Phillips, 1986, 1987).

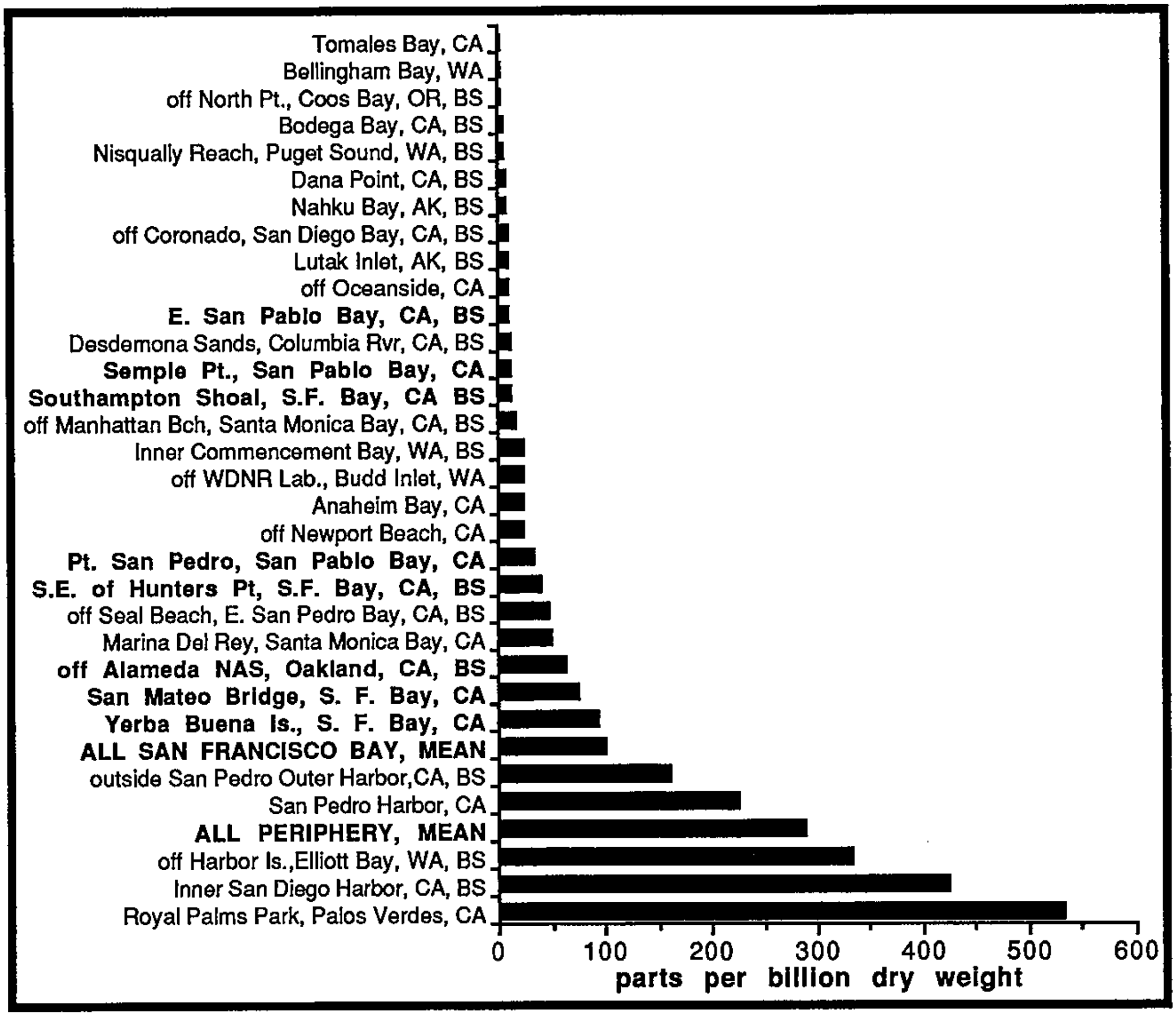


Figure 97. Comparison of PCB concentrations in the surficial sediments of San Francisco Bay, based on historical data (from Table 34), to concentrations in the surficial sediments of NOAA NS&T Program, 1984 Benthic Surveillance (NOAA ,1987a) and 1986 Mussel Watch (Boehm et al., 1987) sites along the Pacific Coast. NS&T Program sites are listed in lower-case print; Benthic Surveillance sites are indicated by a BS after the site name) .

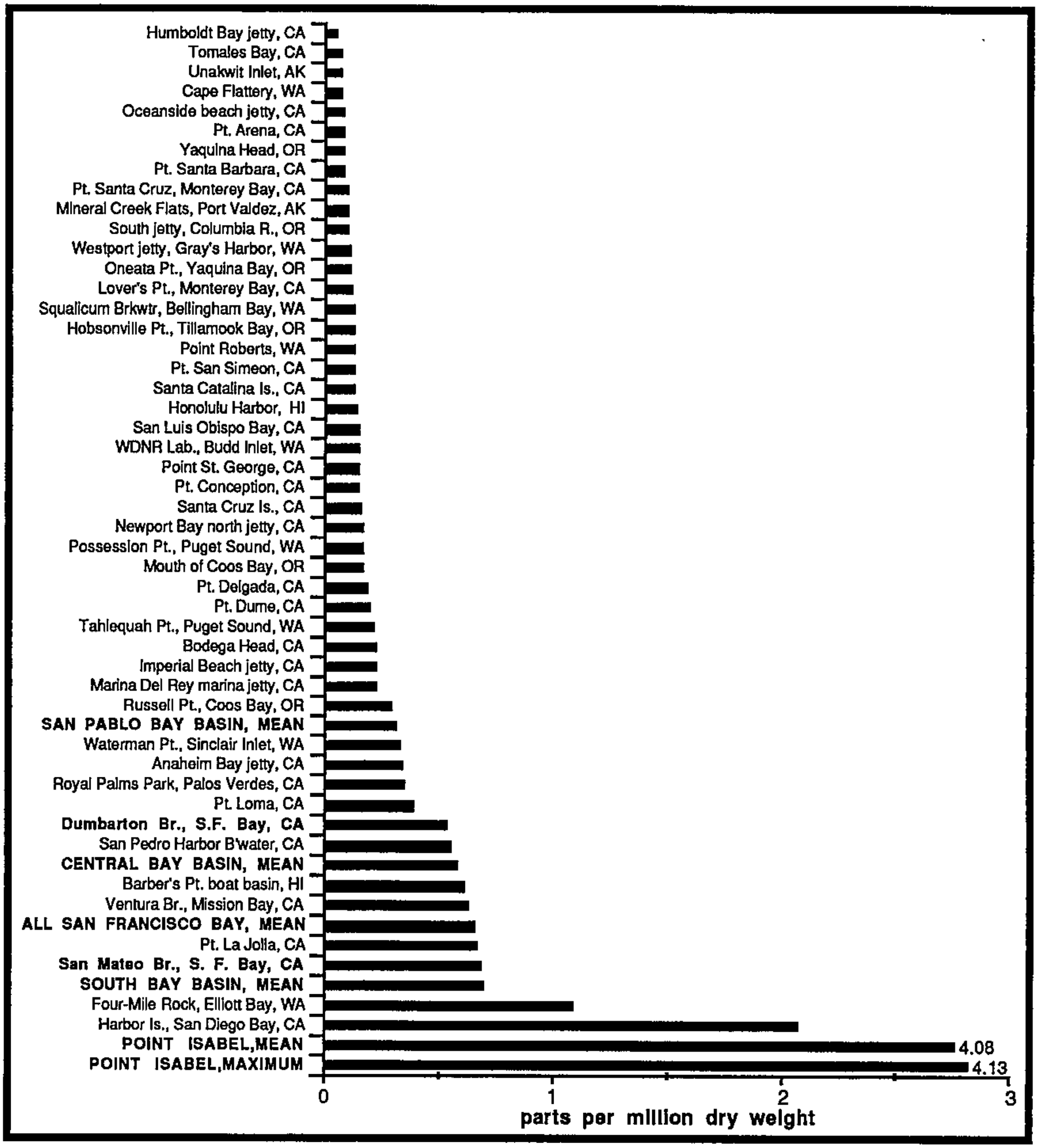


Figure 98. Mean PCB concentrations in resident mussels (Mytilus edulis, M. californianus) from NS&T Program sites (Boehm et al., 1987) sampled in 1986 (n=3) compared to mean concentrations in mussels calculated from historical (1975-1986) data for San Francisco Bay (from Table 37). Areas for which historical data are shown are listed in upper case bold print. NS&T Program Mussel Watch sites are listed in lower case; those in the Bay in bold print.

A SUMMARY OF SEDIMENT BIOASSAY DATA

Bioassays of bulk sediments and sediment elutriates are generally performed to determine the potential bioavailability and toxicity of sediment-bound contaminants. Since chemical analyses alone provide no information on the toxicity of the sediments, bioassays are a helpful and complementary tool for assessing sediment quality.

Bioassays are performed in a laboratory under controlled conditions. They are usually performed to test for acute toxicity with percent mortality as the observed end point. However, some recently developed bioassays include sublethal and/or genotoxicity end points, such as reduced growth and incidence of chromosome damage. They are usually short term (2 to 10 days). They often employ a small invertebrate as the test organism, though fish, algae, and bacteria have also been used.

Relative to Puget Sound, where over 600 sediment samples have been tested in bioassays (Long, 1985), a very small number of these tests has been performed thus far in the San Francisco Bay system. The two tests for which the most data exist are the bulk sediment bioassay with the amphipod *Rhepoxynius abronius* and the elutriate bioassay with the larvae of either the mussel *Mytilus edulis* or the oyster *Crassostrea gigas*.

A. Bulk sediment bioassays with the amphipod *Rhepoxynius abronius*.

This is a 10-day test of acute mortality using the protocol of Swartz et al., 1985. Twenty animals per replicate and usually five replicates per sediment sample are tested to determine the number of survivors. Avoidance of the test sediments and inability of the animals to re-bury in clean sediments can also be tested. Approximately 200 grams of sediment are added to a 1-liter beaker, the beaker is then filled with clean seawater from the laboratory, and finally, the amphipods are placed in the beakers for the 10-day test. The amphipods are bottom-dwellers, so they seek and burrow in the sediments.

Date are available from tests of 77 samples collected at 26 sites in south Bay (Baumgartner et al., unpublished manuscript); several sites near Hunters Point, Treasure Island, and Alameda (U.S. Navy, 1987; ESA, 1987); a site each in San Pablo Bay, off Oakland and in Islais Creek Waterway (Chapman et al., 1986); a site at the Alcatraz disposal area (ENSECO, 1986); a site in Richmond Harbor (E.V.S. Consultants, 1986); and several "reference" locations nearby and in Oregon and Washington.

Figure 99 illustrates the mean number of survivors per site and the number of samples that were tested per site in replicated bioassays by a variety of laboratories. The samples from among the Hunters Point slips, off Treasure Island, and in the Alameda Harbor were collected with a coring device; the test sediments were pooled from portions of several cores taken from various subsurface strata (U. S. Navy, 1987; ESA, Inc., 1987). The samples from San Pablo Bay, Islais Creek Waterway, and off the Alameda NAS were surficial sediments (upper 2 cm) taken with a van Veen grab sampler (Chapman et al.,1986). The Alcatraz Disposal site sample was composited from five grab samples taken from the upper 1 foot of sediment (ENSECO, 1986). The Richmond Harbor sample was taken with a coring device from four sites and composited (E.V.S. Consultants, 1986). The sediment depth was not specified. The samples from reference sites in Yaquina Bay, Oregon and West Beach on Whidbey Island in Puget Sound were surface intertidal sediments.

The samples from off Treasure Island and from very deep in the cores off Hunters Point and in Islais Waterway were clearly most toxic to the amphipods. The sediments from the Islais Creek site were significantly more toxic than those from the Puget Sound reference site (p=0.05). Those from the San Pablo Bay and Alameda NAS sites were not (p=0.05). The shallow cores from among the Hunters Point slips and in the Alameda Harbor were also more toxic than those from elsewhere in the Bay (e.g, Golden Gate) and from the reference sites in Oregon and Puget Sound. However, given that these sediments and those from the Alcatraz Disposal Site and Richmond Harbor were composites of multiple samples taken from varying sediment depths, the data cannot be considered strictly equivalent to those from the surficial grab samples.

Dilution of potentially toxic sediments by relatively clean sediments and contamination of clean sediments may have occurred in the compositing. Although all the data are from samples collected in 1985, 1986, and 1987, they may represent toxic responses to contaminant inputs from very different periods since different sediment strata were sampled in the various studies.

The surface and near-surface samples from offshore in the Pacific Ocean and near Golden Gate were equivalent in toxicity to those from Yaquina Bay and Puget Sound reference sites, suggesting they could be used in the future as reference sites for sediment toxicity tests. Those from off the Alameda NAS and in San Pablo Bay showed minimal toxicity.

Figure 100 illustrates the data from one laboratory, the U.S. EPA Environmental Research Laboratory in Newport, Oregon, resulting from testing unreplicated samples from 26 sites in south Bay (Baumgartner et al., unpublished manuscript). There were no survivors following exposure to the samples from two sites. Fewer than 75 percent of the amphipods survived the tests in all but six of the samples. Four of these six samples had less than 80 percent silt and clay, whereas most (20 of the 26 samples) had over 80 percent silt and clay. The average number of survivors (12) in samples from near Hunters Point was similar to that (11) for all 26 samples.

No data exist for the Bay for portraying temporal trends in sediment toxicity to *R. abronius.*

The range in responses of the amphipod bioassay to sediment samples from the Bay is similar to that observed elsewhere along the Pacific Coast. The most toxic sediments in the Bay are mostly from the harbors and among the shipyard slips. The data from samples from Islais Waterway, near Treasure Island and among the Hunters Point slips in which 6 to 15 amphipods survived are comparable with those from City Waterway (n = II, 10.6 survivors) and Hylebos Waterway (n = 66, 9.5 survivors) near Tacoma, Washington (Long, 1985). In a reference site (Carr Inlet) in Puget Sound, 17.3 survivors (n = 4) were observed; in the central basin of Puget Sound, 16.9 to 18.4 survivors (n = 6 to 14) were observed in seasonal sampling. In Southern California Bight sediments, a mean of 17.8 (n = 9) and 19.4 (n = 8) survivors was documented in 1980 and 1983, respectively (Swartz et al., 1986). However, the average number of survivors observed in tests performed thus far with samples from the basins of the Bay, appears to be unexpectedly low when compared to samples from open embayment sites in Puget Sound and from sites off Southern California. For example, the average of 11 survivors in the 26 samples tested by U.S. EPA is below the 16 to 18 survivors in samples in the central basin and uncontaminated embayments of Puget Sound tested by various laboratories.

Animals exposed to sediments in bioassays respond to the mixture of available contaminants in the samples, not to just one of the contaminants. Some of these contaminants are detected and quantified in chemical analyses, others are not.

Conversely, some chemicals bound to particulate matter may not be available to biota, yet they can be quantified by chemists following solvent or hot acid extractions. Also, *Rhepoxynius abronius* is an inhabitant of sandy habitats and is known to be sensitive to very high concentrations of some fine-grained sediments, such as clays. Therefore, because of these and other problems, attempts to identify the contaminant(s) responsible for sediment toxicity are not always fruitful through statistical treatments of synoptic toxicity and chemical data.

Nevertheless, strong correlations occurred between the sediment bioassay results and chemical data from Chapman et al., 1986 (Table 38). As survival in *Rhepoxynius abronius* decreased among the nine stations, the concentrations of many of the chemicals increased. Particularly strong correlations occurred between the amphipod results and the concentrations of lead, copper, pesticides, total organic carbon, and sulfide. While these correlations do not establish the causes of the toxicity observed in the bioassays, they establish that many of the contaminants co-vary in concentrations, and together, they occur in relatively high concentrations in samples that were also toxic.

Similarly, Spies (in U.S. Navy, 1987) found that bioassay results with five species were correlated with several chemicals in sediments sampled at Hunters Point, Alameda, and Treasure Island. However, the correlations between chemical concentrations and *Rhepoxynius* survival were often positive, suggesting that survival improbably increased with increasing contamination. A strong negative correlation was seen, on the other hand, between cadmium concentration in bivalves exposed to the sediments and *Rhepoxynius* survival. All the samples tested in this study were toxic to *Rhepoxynius*. All chemical analyses suffered from use of high detection limits. If, however, the detection limits reflected or approximated actual concentrations of contaminants, the concentrations of PAHs were within the range (Table 39) that co-occurred with highest mortalities to *Rhepoxynius* in the study by Chapman et al. (1986).

Table 39 portrays the means and ranges in concentrations of selected contaminants associated with or co-occurring with ranges in survival of *R. abronius* from the data for nine stations (Chapman et al., 1986). In this analysis, the bioassay data were examined to determine modes in the frequency of bioassay results. Three modes were observed: 2 to 10, 11 to 15, and 16 to 20 survivors out of 20 animals. The chemical data for selected analytes from these samples were then examined to determine co-occurrence of bioassay data and chemical concentrations. Chemical concentrations were highest at the station in which a mean of 2 out of 20 amphipods survived. Low molecular weight PAH concentrations ranged from 0.22 to 3.16 ppm in samples in which 15 or fewer amphipods survived. Contaminant levels were lower in samples from stations in which more amphipods survived. These data must be viewed with caution since the sample size (nine) was small and since toxicity in Islais Creek Waterway samples may have been caused, in part, by high concentrations of sulfide. The sediments there were highly organically enriched. However, the data in this table can be used as the beginning of an effort to establish the sediment contaminant levels that may be of concern in San Francisco Bay. For example, it would be useful to examine other data as they become available to determine if 15 or fewer survivors always occur in bioassays of sediments with a mean of 1.30 ppm low molecular weight PAHs or greater.

Data from 10 samples from south Bay, in which both chemical analyses and bioassays were performed (Baumgartner, et al., unpublished manuscript), showed either no significant positive correlations or negative correlations between toxicity and contaminant concentrations. (Trace metals data were not yet available for inclusion in this manuscript.) All the bioassay results showed toxicity and the chemical data were relatively monotonous among the samples. One notable exception was the sample taken near Hunters Point in which only 6 amphipods out of 20 survived, and high molecular weight PAHs exceeded the mean of those in all the other samples by a factor of 8 times (13.7 ppm vs 1.7 ppm). Since this survey did not include many samples from grossly contaminated areas, a large range in response in the bioassays and chemical analyses was not observed.

B. Elutriate bioassays with the larvae of the mussel *Mytilus edulis* and the oyster *Crassostrea gigas*.

The data from bioassays with the larvae of these two bivalve species have been pooled since they involve use of the same methods and since the two species are similar in sensitivity (Peter Chapman, personal communication, 1987). Two distinct methods of producing elutriates for use in bioassays with bivalve larvae have been used in the Bay. The method of Chapman and Morgan (1983) was used in tests of surficial sediments by Chapman et al. (1986) and Bendix (1987). The method of the U.S. EPA/ACOE Implementation Manual was used in tests performed by Marine Bioassay Laboratories (1987); the U.S. Department of Navy (1987); ESA, Inc. (1987); and ToxScan, Inc. (1987). The former method involves testing 20 grams of sediments per liter of seawater, whereas the latter involves testing one part sediment to four parts seawater (roughly 250 grams sediment per liter of seawater). Both involve shaking the sediment/water slurry for a specified period, allowing the sediments to settle, and pouring off the supernatant for retention and use in the bioassay. Both percent survival and percent abnormal larvae are observed as end points after 48 hours. Since the latter end point has been reported most frequently and is considered to be most indicative of chemical toxicity (Chapman and Morgan, 1983), those data are summarized in this section. The results of tests using the two protocols are not comparable.

Data resulting from use of the Chapman and Morgan (1983) method indicated that samples from San Pablo Bay were not toxic (Figure 101). They were comparable to a sample from West Beach on Whidbey Island in Puget Sound, a pristine reference area. Samples collected off the Alameda NAS and in Islais Creek Waterway were, in order, increasingly toxic. Those from the Islais Creek site were significantly different from the reference site (p=0.05). Samples from off piers 94/96 and an undescribed central Bay reference site that were frozen before use in the bioassays had extremely high responses. The effects of freezing samples before toxicity testing may result in high variability in the data and questionable comparability with data from the testing of unfrozen samples. Also, these data are suspect since only 50 percent survival was reported in seawater controls. Data resulting from use of the EPA/ACOE Implementation Manual method indicate that samples from among the Hunters Point slips and off Treasure Island were toxic while those from Richmond and Oakland Harbors and an undescribed "offshore" site were not (Figure 102).

Based upon the Chapman and Morgan (1983) method, the mussel larvae bioassay data from grab samples in the Bay showed somewhat higher toxicity than observed in samples from reference areas in Puget Sound (Figure 101). Mean percent abnormal oyster larvae in Samish Bay, Dabob Bay, Sequim Bay, Case Inlet, and Carr Inlet (all n = 4 each) were 1.9, 8.4, 9.7, 9.4, and 13, respectively (Long, 1985), compared to 12.1 and 19.3 for San Pablo Bay and off the Alameda NAS, respectively. Compared to a mean of 28.9 (n=14) percent abnormals in contaminated Hylebos Waterway, Tacoma, Washington, 55.2 percent of the larvae were abnormal following exposure to Islais Waterway samples.

Many measures of contamination at the nine stations sampled by Chapman et al. (1986) correlated strongly with percent abnormal larvae of *Mytilus edulis* in bioassays of the same samples (Table 38). As abnormal *M. edulis* larvae increased among the nine stations, chemical concentrations increased. With the mussel larvae abnormality data, strong associations occurred with high and low molecular weight PAHs, pesticides, PCBs, TOC, sulfide, silver, and chromium. Silver, PAHs, chromium, PCBs, total volatile solids (TVS), and pesticides correlated strongly with decreased mussel larvae survival. It is apparent from these data that many contaminants co-occurred with each other and that they were elevated in concentration at the site (Islais Creek Waterway) where toxicity was high as measured with the mussel larvae bioassay.

To determine the co-occurrence between ranges in bioassay data and associated chemical data, the data were examined in the same manner as described above for the *Rhepoxynius* data. The concentrations of the most highly correlated contaminants that are associated with ranges in bioassay responses are displayed in Tables 40 and 41. The data illustrate the co-occurrence of high levels of contamination associated with high percent abnormal mussel larvae and low percent survival. High percent abnormal larvae in the bioassays occurred in samples with about 3 ppm low molecular weight PAHs, about 12 ppm high molecular weight PAHs, about 200 ppb PCBs, etc. Samples with high percent abnormal larvae were often 3 to 10 times more contaminated than those with low percent abnormal larvae. Low survival was associated with 1.11 to 12.06 ppm high molecular weight PAHs; higher survival was associated with 0.22 to 1.89 ppm in these compounds.

These correlations and associations are to be viewed cautiously, since the sample size (nine stations) was small and since the data were so strongly influenced by the samples from Islais Creek Waterway (an organically enriched and contaminated channel). Also, sulfide content was very high in the Islais Creek Waterway samples, indicative of high organic matter content and reducing conditions that may have contributed to toxicity in the bioassays. Nevertheless, these data may be useful as an initial step in identifying along with future data, the apparent levels of sediment contamination of concern in San Francisco Bay.

Both the concentrations of zinc in sediments and zinc in adult bivalves exposed to the sediments were negatively correlated with percent normal development in bivalve larvae following exposure to elutriates of samples from Hunters Point, Treasure Island, and Alameda (U.S. Navy, 1987). All the bioassays were significantly toxic relative to controls. Copper in the sediments also showed a pattern of increasing concentration with decreasing normal larvae, but the correlation was apparently not significant (Spies in U.S. Navy, 1987).

C. Other Bioassays

A limited variety of other tests of sediment toxicity have been performed on samples from the Bay. Bendix (1987) showed higher toxicity at a central Bay reference site than at sites near piers 94/96 off San Francisco with a Microtox™ bacterial luminescence test. Sediment elutriates (18.9 grams per liter (g/l.)) from the Oakland Inner Harbor were toxic to juvenile *Cancer magister* crabs (Peddicord and McFarland, 1976); whereas samples (250 g/l.) from the Petaluma River channel were not (Marine Bioassay Laboratories, 1984). Samples (250 g/l.) from the Oakland Outer Harbor were not toxic to grass shrimp (*Crangon nigricauda*), shiner perch (*Cymatoyaster aggregata*), or copepods (*Acartia tonsa*) (Marine Biological Laboratories, 1980).

Both sediment elutriate bioassays and solid phase bioassays with the mysid *Acanthomysis sculpta* were performed on samples from Hunters Point, Alameda, and Treasure Island (U.S. Navy, 1987). The elutriate exposures were for 96 hours and the solid phase exposures for 20 days. In the elutriate tests, 0 to 7.7 survivors out of 10 (mean = 3.7, n=4) were observed in Hunters Point samples, 0 to 9.3 survivors out of 10 (mean = 5.1, n=6) in Treasure Island samples, compared to a mean of 7.7 (n=2) survivors at Alameda. In the solid phase bioassays, 15.4 to 18.6 survivors out of 20 (mean = 17, n=7) were observed in Hunters Point samples, 12.6 to 17 survivors out of 20 (mean = 15, n=6) in Treasure Island samples, compared to a mean of 13.1 (n=2) at Alameda. The same elutriate samples were also tested with the sanddab *Citharichthyes stigmaeus* in 96-hour bioassays. A range of 0 to 9 survivors out of 10 (mean = 5.5, n=8) was observed with Hunters Point samples, 8.7 to 10 survivors out of 10 (mean = 9.6, n=6) with Treasure Island samples, and a mean of 9.8 (n=2) with Alameda samples. Using a preponderance of evidence from these bioassays and the amphipod and oyster larvae bioassays, Chapman (in U.S. Navy, 1987) showed that Hunters Point sediments were the most toxic and Alameda sediments were the least toxic.

Table 38. Results of correlation analyses between synoptically collected contaminant data from nine stations (from Chapman et al.,1986). Significant correlations exceed .666 (at alpha = .05).

	Rhepoxynius abronius survival	*Mytilus edulis* larvae percent abnormalities	*Mytilus edulis* larvae survival
LMWPAH	- 0.782	0.982	- 0.755
HMWPAH	-0.743	0.983	-0.770
Hg	- 0.335	0.828	- 0.646
Cu	- 0.874	0.926	- 0.691
Pb	- 0.915	0.905	- 0.666
Cr	- 0.656	0.935	- 0.765
Ag	- 0.717	0.983	- 0.807
t Pesticides	- 0.831	0.968	- 0.740
t PCBs	- 0.571	0.953	- 0.740
TOC	- 0.827	0.929	- 0.644
Sulfide	- 0.799	0.968	- 0.737
TVS	- 0.785	-0.898	- 0.751
% Solids	- 0.517	0.620	- 0.666
% Fines	- 0.376	0.402	- 0.406

LMWPAH = the sum of 10 low molecular weight polynuclear aromatic hydrocarbons;
HMWPAH = the sum of 7 high molecular weight polynuclear aromatic hydrocarbons;
Pesticides = the sum of 17 chlorinated pesticides;
TOC = total organic carbon;
PCBs = polychlorinated biphenyls;
TVS = total volatile solids

Table 39. Mean (and ranges) in contaminant concentrations in sediments from nine stations associated with three ranges in survival of Rhepoxynius abronius (from Chapman et al., 1986).

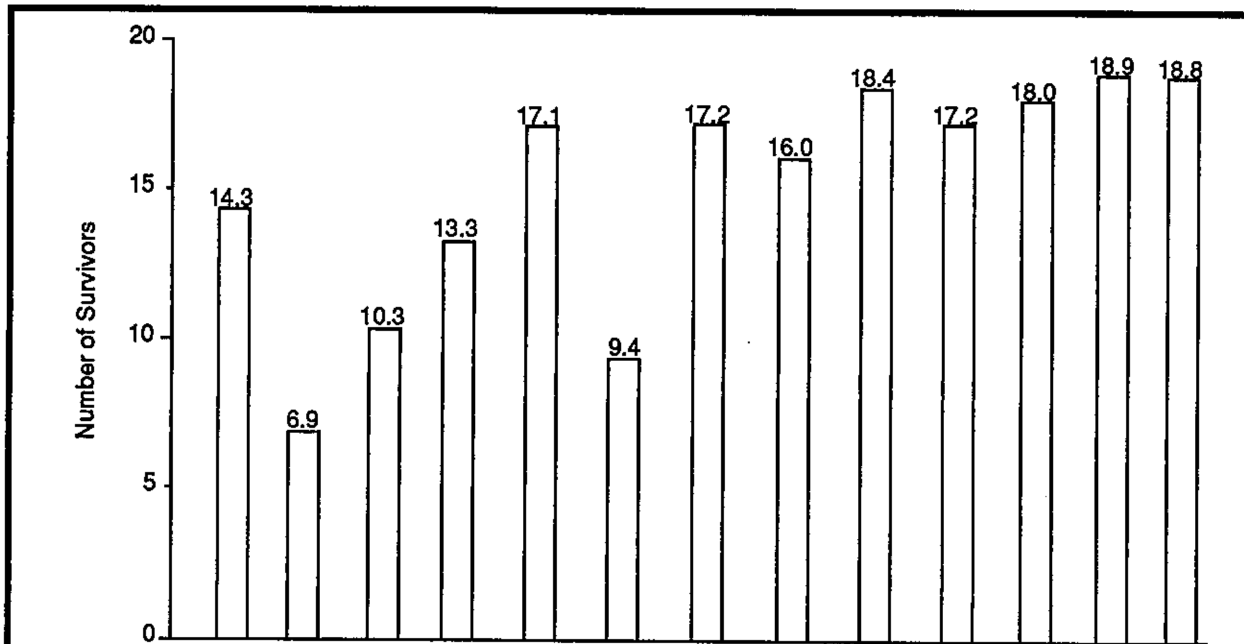
Rhepoxynius abronius survival out of 20	N	LMWPAH ppm	HMWPAH ppm	Pesticides ppm	Pb ppm	Cu ppm	Ag ppm
1 (1 - 10)	1.	3.16 (3.16)	12.06 (12.06)	8.26 (8.26)	223 (223)	130 (130)	8.1 (8.1)
14.3 (11 - 15)	3	1.3 (0.22 - 2.76)	5.66 (0.67 - 11.82)	3.20 (0.92 - 6.24)	63 (25 - 115)	73 (53 - 98)	4.73 (1.6 - 8.6)
18.1 (16 - 20)	5	0.28 (0.03 - 0.43)	1.12 (0.22 - 1.89)	1.08 (0.63 - 1.69)	26 (18 - 33)	43.6 (30 - 51)	1.62 (0.9 - 2.4)

Table 40. Mean and (ranges) in contaminant concentrations in sediments from nine stations associated with two ranges in percent abnormal larvae in *Mytilus edulis* (from Chapman et al., 1986).

Mytilus edulis		LMWPAH	HMWPAH	PCBs	Pesticides	Cr	Ag
percent abnormal larvae	N	ppm	ppm	ppb	ppb	ppm	ppm
66.8 (66 - 68)	2	2.96 (2.76 - 3.16)	11.94 (11.82 - 12.06)	217.55 (179.8 - 255.3)	7.25 (6.2 - 8.3)	140 (134 - 146)	8.35 (8.1 - 8.6)
18 (8 - 32)	7	0.36 (0.03 - 0.92)	1.54 (0.22 - 4.48)	25.97 (5.7 - 57.3)	1.25 (0.63 - 2.45)	90.14 (72 - 110)	1.96 (0.90 - 4.0)

Table 41. Mean and ranges in contaminant concentrations in sediments from nine stations associated with three ranges in survival of *Mytilus edulis* larvae (from Chapman et al., 1986).

Mytilus edulis percent relative survival	N	LMWPAH ppm	HMWPAH ppm	PCBs ppb	Pesticides ppb	Cr ppm	Ag ppm
16.1 (3.2 - 33.5)	5	1.51 (0.32 - 3.16)	6.20 (1.11 - 12.06)	109.2 (26.6 - 255.3)	3.86 (1.08 - 8.26)	113 (85 - 146)	4.96 (1.7 - 8.6)
52.3 (49.1 - 56.9)	3	0.23 (0.03 - 0.43)	0.93 (0.22 - 1.89)	20 (5.7 - 36.8)	1.08 (0.63 - 1.69)	86.7 (72 - 95)	1.50 (0.9 - 2.0)
82.7 82.7	1	0.21 (0.21)	0.85 (0.85)	11.1 (11.1)	0.74 (0.74)	86 (86)	1.1 (1.1)



Site	Hunters Point	Hunters Point	Treasure Island	Alameda Harbor	San Pablo Bay	Islais Waterway	off Alameda NAS	Alcatraz Disposal Site	Golden Gate	Richmond Harbor	"Offshore"	Yaquina Bay, Oregon	West Beach, Washington
Number of samples	3	2	6	2	10	10	10	1	1	1	1	2	2
Sampler	cores	cores	cores	cores	grab	grab	grab	grab	grab	cores	dredge	cores	cores
Date	1987	1987	1987	1987	1985	1985	1985	1985	1985	1986	1987	1985/6	1985/6
Depth in sediments	0 to -38ft.	-40ft. to-47ft.	0 to -32ft.	5ft to -32ft.	-2cm.	-2cm.	-2cm.	-1ft.	-1ft.	unk.	-1ft.	sfc.	sfc.

Figure 99. Mean number of survivors (out of an initial 20) of Rhepoxynius abronius after 10-d exposure to sediments (see text, p. 205, for references).

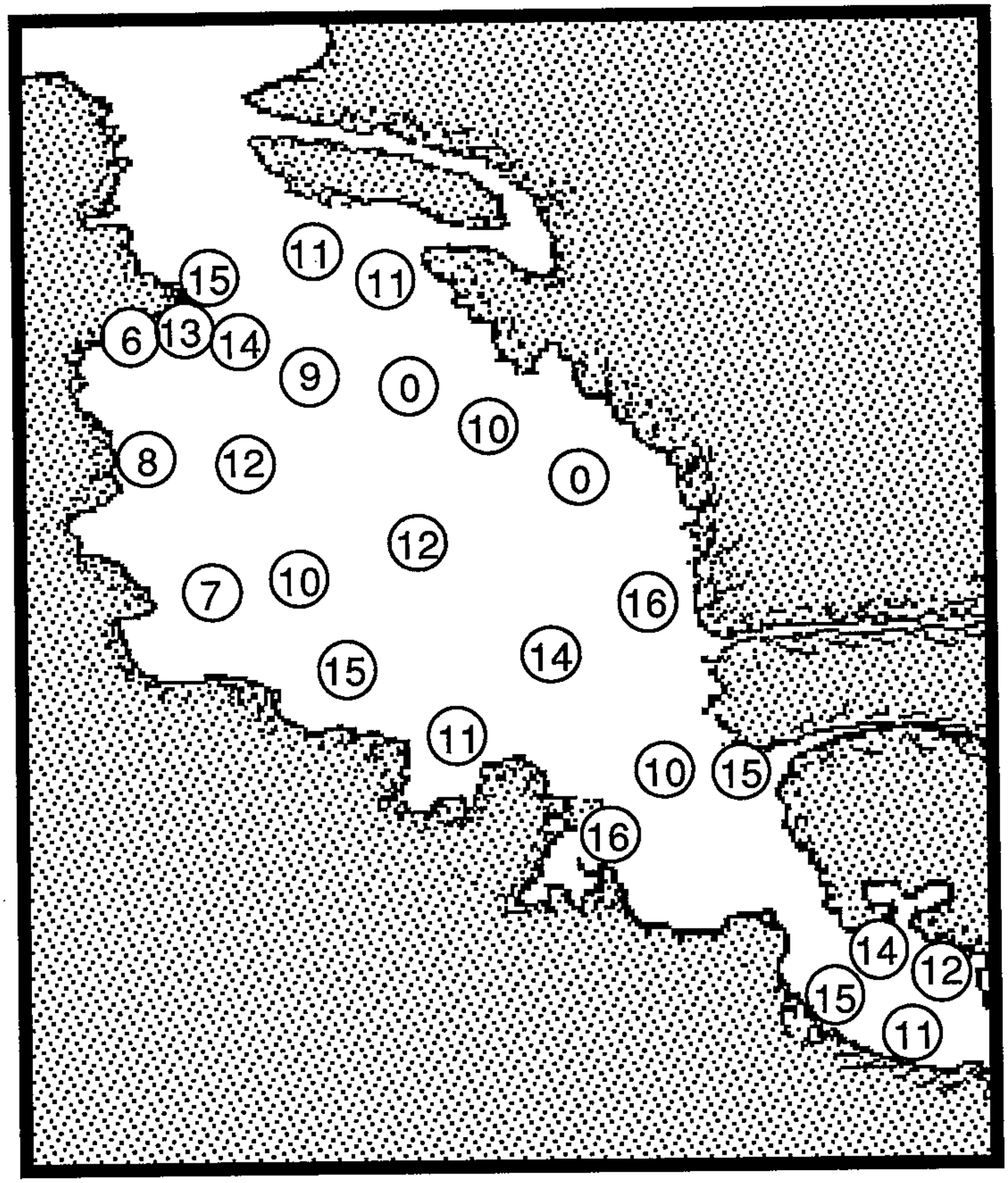
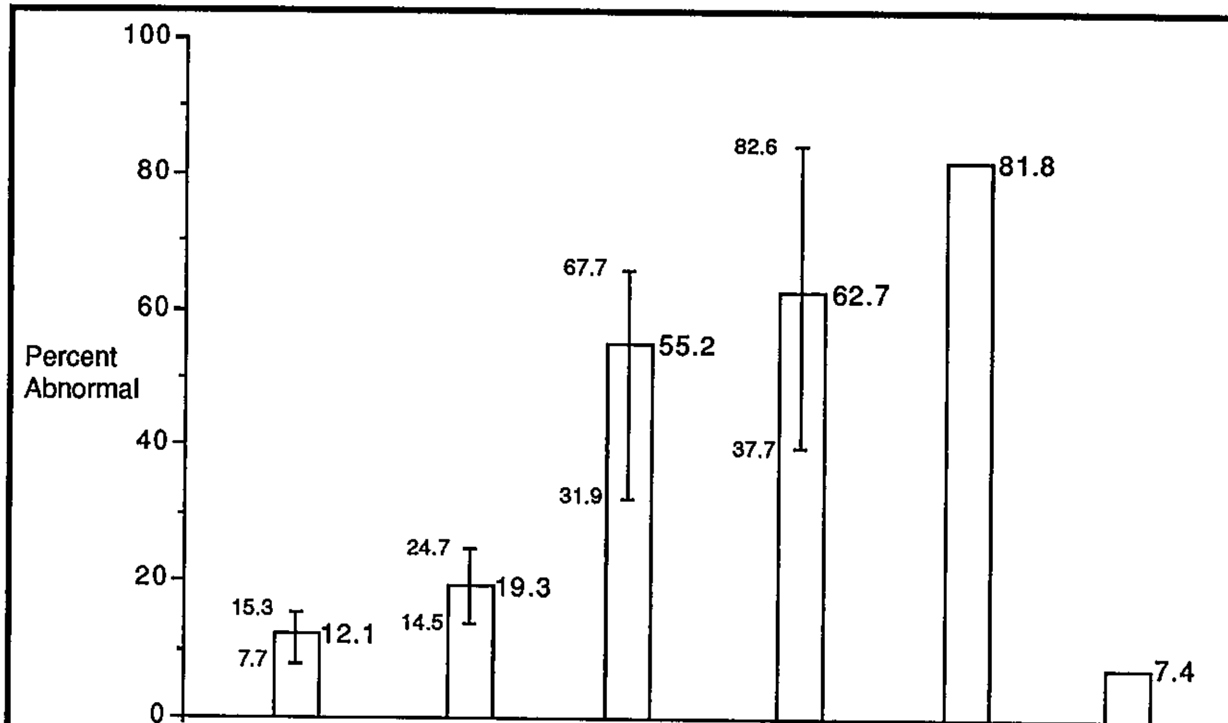


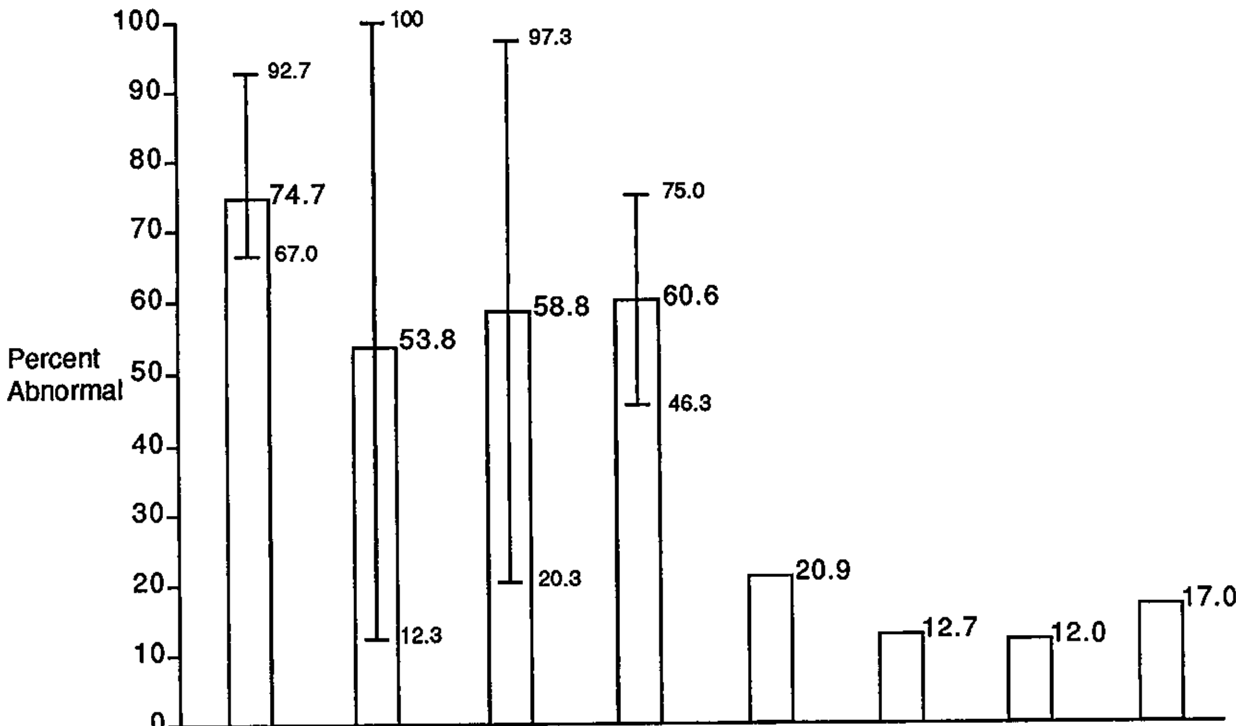
Figure 100. Survivors (out of 20) of Rhepoxynius abronius exposed for 10 days to surficial sediments collected by U.S. EPA (Baumgartner et al., unpublished manuscript) in September 1986.



Site	San Pablo Bay	off Alameda NAS	Islais Water-way	off Piers 94/96	Central Bay	West Beach, Wash.
Number of samples	3	3	3	9	1	1
Sampler	grab	grab	grab	core*	core*	core
Date	1985	1985	1985	1987	1987	1985
Depth in sediments	-2cm.	-2cm.	-2cm.	unk.	unk.	sfc.

*Samples frozen before testing

Figure 101. Mean (and range) percent abnormal mussel larvae after 48-hour exposure to 20g./l. sediment elutriates. (See text, p. 207, for references.)



Site	Hunters Point (O)	Hunters Point (O)	Hunters Point (M)	Treasure Island (O)	Richmond Channel (O)	Oakland Inner Harbor (M)	Oakland Outer Harbor (M)	"offshore" (O)
Number of samples	3	6	2	2	1	1	1	1
Sampler	cores	cores	cores	cores	unk.	unk.	unk.	unk.
Date	1987	1987	1987	1987	1987	1987	1987	1987
Depth in sediments	0 to -38ft.	0 to -17.5 ft.	-40 to -47 ft.	0 to -32 ft.	unk.	unk.	unk.	unk.

Figure 102. Mean and (range) percent abnormal mussel (M) and oyster (O) larvae after 48-hour exposure to 4:1 water/sediment elutriates (see text, p. 207, for references).

13

A SUMMARY OF FISH HISTOPATHOLOGY DATA

It has long been recognized that certain chemicals have the ability to induce cancerous growths, as well as other pathological and histopathological tissue disorders in test organisms. However, some histopathological conditions can be caused by natural stress factors such as viruses, poor nutrition, parasites, physical injury, etc. Surveys of feral fish and bivalves have reported a co-occurrence or correlation between incidences of neoplastic (cancerous) or pre-neoplastic (probably pre-cancerous) disorders and the concentration of observed trace contaminants in either the adjacent sediments or the animals themselves (Malins et al., 1984). Therefore, histopathological examinations of tissue lesions have become a tool in regional pollution assessments by NOAA and others.

Demersal (bottom-dwelling) fish, which are either in frequent physical contact with sediments much of the time and/or feed on benthic prey, are thought to be reasonable integrators of contaminant exposures throughout their migratory range. Because sediments accumulate numerous contaminants, bottom-dwelling flatfish receive a relatively high exposure to mixtures of sediment-associated chemicals that may be present within a region. Since each species reacts differently to various contaminants, some species appear to be more susceptible to lesion generation than others. Determinations of temporal and geographic trends in prevalence of certain disorders in selected species can serve as biological indicators of trends in exposure to contamination, provided sufficient sample sizes are available.

Three species of bottom fish and bivalves from the Bay have been examined for pathological and histopathological disorders. There are historical data for one particular pathological disorder--skin papillomas--in English sole (*Parophrys vetulus*). More recent histopathological data (1984-85) for conditions that have been associated with contamination are presented for the other two species of fish. This chapter will summarize temporal and geographical trends in prevalence data and the relationship, if any, between prevalence of disorders and contaminants.

A. English Sole Skin Tumors

As early as 1922, the presence of "wart-like dermal swellings" in English sole (*Parophrys vetulus*) in San Francisco Bay was noted by Hubbs (in Harold and Innes, 1922), who reported approximately a 15 percent prevalence rate. Hesteroff studied tumors in fish from the Bay in 1953 (in Kelly, 1971). He reported a prevalence of between 16 and 32 percent in trawls of the central Bay English sole, and also noted that the condition seemed to be unique to the English sole.

Later sampling by Cooper and Keller (1969) encompassed all of the south and central Bays plus the southern end of San Pablo Bay. They examined 15,739 English sole during the year-long study (1965-66) and they reported a seasonality to the prevalence of tumorous fish with a peak in July. This condition affected primarily young fish (median length about 80 mm). Tumors were not observed in fish over 200 mm. They reported no difference in the size of tumorous and non-tumorous fish nor a difference between the mean size of fish with one, two, and three or more tumors. They composited their data from different sampling stations and determined that the prevalence among central Bay fish was nearly twice that of the south Bay fish: 15.5 percent versus 8.9 percent.

Another collection of over 5,000 fish was made during 1969-70 by Kelly (1971). Two distinct areas of comparable water depth were sampled: east of Treasure Island in central Bay and north of the San Rafael Bridge in southern San Pablo Bay. Kelly found a 9.6 percent incidence at the central Bay site, which is comparable to Cooper and Keller's data, and an incidence of only 1.7 percent at the more northerly site, considerably lower than Cooper and Keller's value. Special collections at the southern site showed a clear tendency for younger, smaller fish that occupy shallower waters to have higher prevalences than older fish in deeper waters. Specifically, of the fish in 1 to 1.5 fathoms, 13 percent were tumorous; in 1.5 to 2.0 fathoms, 5.7 percent were tumorous; and none were found with tumors in 4 to 6 fathoms of water.

Kelly also investigated the development of tumors from their precursor angioepithelial nodules. He found that epidermal papillomas did not develop except from nodules, and that the predominant fate (70 percent) of both the nodules and papillomas was sloughage. This observation helps explain why older, larger fish were not observed with these disorders. Kelly further investigated the etiology (causal agent) of the tumors via microscopy. A unique cell, the X cell, was detected in nodules and papillomas, but not in normal tissue. The etiology of the X cell is still debated (Linda Rhodes, personal communication, 1987), yet it is generally considered to be parasitic (possibly a virus, or a protozoan amoeba).

There appears to be no data available to assess temporal trends in the prevalence of papillomas. Given the differences between sampling designs of the various studies, rigorous testing of the data is not practical. The rate of 15 percent given by Hubbs in 1922 seems to approximate the prevalence of this condition among the Bay's English sole at that time. No similar analyses of English sole have apparently been performed since 1970.

B. Starry Flounder Histopathology

The NS&T Program (NOAA, 1987a) and the California State Water Quality Control Board (Spies et al., 1985b; Myers et al., 1983) have sampled starry flounder (*Platichthys stellatus*) on five separate occasions during 1983 through 1985 to determine microscopically the prevalence of histopathological tissue disorders. The end points of these studies vary, yet the basic trends observed are consistent. Over 200 starry flounder have been examined between these three investigations.

Spies et al. (1985b) categorized abnormalities of the liver tissue (in a rating index from 0 to 3) according to their severity and etiology. Mean data for four sites for this "liver grade" index (LGI) are calculated as the sum of grade scores divided by the total number of fish times 100. A high mean LGI indicates poor average liver health of the fish sampled (Figure 103). The sites were in western San Pablo Bay, off Berkeley, off Oakland, and off Alameda. He also enumerated the fish that were severely affected, and those with neoplastic or pre-neoplastic conditions. For all three of these end points, the sites located off Berkeley and Oakland had the highest prevalences, while the site in San Pablo Bay had the lowest. Spies also examined the occurrence of melanin macrophage centers of the liver, an age-related disorder of abnormally high melanin storage. A total of 213 fish were examined, with those from stations located near Berkeley, Oakland, Alameda, and Richmond composited together. These fish experienced a 0 to 43 percent incidence rate, depending on size, while the range in San Pablo Bay fish was only 0 to17 percent, and was lower for all but the largest size class (20 fish total) than the mid-Bay fish. Still, the difference between the two areas cannot be considered statistically significant (paired T-test, $p=0.25$).

Myers et al. (1983) examined 39 starry flounder in a screening survey in 1983, primarily from the central Bay, and found a variety of infestation conditions. However, no neoplastic or pre-neoplastic conditions, nor any other conditions that are considered commonly associated with contamination, were found.

The Benthic Surveillance Project of the NS&T Program includes examinations of bottom fish annually to determine the prevalence of histopathological disorders. Starry flounder have been sampled off Hunters Point, at Southhampton Shoal, in eastern San Pablo Bay, off Oakland, and in Bodega Bay. In 1984, the first year of sampling, the Project found 1 fish out of 30 examined in eastern San Pablo Bay and 1 out of 16 at Southampton Shoals with foci of cellular alteration (a pre-neoplastic condition) in livers. No neoplastic conditions were found at any other site. The prevalence of degenerative and proliferative disorders in kidneys was higher. Nearly 40 percent of the fish from Southhampton Shoal had kidney degeneration/necrosis, compared to about 20 percent off Hunters Point, 10 percent in San Pablo Bay, and none in 13 fish from Bodega Bay. Compared to the other sites, the fish from Southhampton Shoal were larger and mostly females. Proliferative disorders of the liver occurred in a few of the 28 fish caught off Hunters Point and in 1 fish from Bodega Bay; none was found at the other sites. Thus far, there are insufficient data to determine potential temporal trends in histopathological conditions of the starry flounder. As data from subsequent years become available, temporal trends analyses will be feasible.

C. White Croaker Histopathology

The Benthic Surveillance Project of the NS&T Program (NOAA, 1987a) also examined white croaker (*Genyonemus lineatus*) caught in 1984 from three of the four sites in the Bay and in Bodega Bay. No liver disorders were observed in any of the 72 fish caught in the Bay or in the 37 fish from Bodega Bay. There were two fish each (7 percent) at the Southampton Shoals site and the Oakland site with degenerative disorders of the kidney; about 5 percent of the fish from Bodega Bay had these disorders. The prevalences of proliferative disorders of the kidney were 3 percent at Southhampton Shoal, 10 percent at Oakland, and about 7 percent at Bodega Bay (Figure 104). None was found in white croaker from the Hunters Point site. The differences between sites for either condition are not significant (X^2 test with $.70<p<.80$ and $.50<p<.60$, respectively). There are insufficient data to determine potential temporal trends in histopathological conditions of the white croaker. As data from subsequent years become available, temporal trends analyses will be feasible.

D. Relationships between Disorders and Tissue and Sediment Chemistry

Two of the previously mentioned studies included both sediment and tissue chemistry data as portions of their monitoring parameters: those of Spies et al. (1985b) and the NS&T Program (NOAA, 1987a). Simple, linear relationships between prevalence of histopathological observations and residue levels in the livers, as determined by correlation analysis, were performed (Tables 42 and 43). Due to low sample sizes and inherently high variation in samples, this is not a rigorous test of the data.

Both data sets indicate strong correlations, as expected, among particular sediment parameters and between concentrations of some residues in tissue and in sediments (e.g., tDDT in the liver versus sediment tDDT and/or tPCBs). However, few statistically significant relationships were found between the prevalence of pre-neoplastic or neoplastic disorders and tissue contamination. Spies' data shows a linear relationship between prevalence (as percents) and sediment PAHs. The NS&T Program shows a correlation between foci of cellular alteration in white croaker and the level of "naphthalene-like" aromatic hydrocarbon metabolites in the bile. Both data sets also show correlations between prevalence of pre-neoplastic and neoplastic disorders and sediment levels of copper of equal magnitude, but with inverse trends. This latter observation highlights the inability of statisitics to resolve, given small sample sizes and high variability, environmental factors that influence the prevalence of histopathological conditions.

Non-rigorous graphical examination of several parameters from both data sets points out further trends. In the NS&T Program data, the Oakland and Hunters Point sites frequently clustered together, and the San Pablo Bay and Southhampton Shoals sites also clustered together. With Spies' data, such patterns were less prominent.

The Mussel Watch Program, conducted by U.S. EPA during 1976-77, also investigated pathological conditions of the three bivalve species monitored. No raw pathological data from this program have become available; however, reviews of the national data set (Reynolds, 1981) state that no strong correlations existed between pathological conditions and tissue chemistry.

E. Summary

Among the fish examined thus far, there appears to be a reccurring trend of relatively high prevalences of disorders in the eastern central Bay near Berkeley and Richmond and in south Bay near Oakland. San Pablo Bay fish usually have relatively low prevalences. Temporal trends analyses are not yet feasible until data from the NS&T Program for 1985 and later are available.

Determining the specific etiology of observed histopathological conditions in feral organisms is rarely possible since they are exposed to numerous, potentially adverse, stimuli (e.g., nutritional, infectious, chemical, physical, etc.). Only a portion of these stimuli have been measured or are measurable. While some studies have demonstrated logical or expected statistical relationships between chemical and histopathological parameters, few <u>strong, consistent</u> relationships over large geographic areas have been demonstrated (Mix, 1986; Reynolds et al., 1981). Physiological stress manifested as histopathological disorders may be the result of environmental factors beyond bulk chemistry that have not yet been considered. And an organism's response to these synergistic and antagonistic stress factors, which includes exposure to multiple xenobiotic contaminants, is more complicated than has been previously modelled or more complicated than statistics are able to discern.

Table 42. Correlation matrix of chemical analytes and histopathological measures in starry flounder (*Platichthyes stellatus*) (n=4) (NOAA, 1987a).

	SEDIMENT						LIVER		BILE		Kidney
	PCB	DDT	PAH	Cu	Cr	Pb	PCB	DDT	B(a)p[a]	Naph[b]	Degeneration
Sediment											
DDT	0.987										
PAH	0.622	0.490									
Cu	0.935	0.965	0.380								
Cr	0.648	-0.594	-0.614	-0.361							
Pb	0.908	0.955	0.271	0.898	-0.622						
Liver											
PCB	0.658	0.531	0.998	0.415	-0.649	0.321					
DDT	0.940	0.911	0.663	0.772	-0.869	0.877	0.703				
Bile											
B(a)p	-0.476	-0.501	-0.158	-0.702	-0.353	-0.335	-0.157	-0.148			
Naph	-0.955	-0.919	-0.719	-0.913	0.483	-0.759	-0.742	-0.831	0.642		
Kidney Degen.	0.223	0.203	0.202	-0.051	-0.858	0.356	0.235	0.536	0.745	0.017	
Liver Foci of cellular alteration	-0.836	-0.820	-0.562	-0.902	0.167	-0.636	-0.576	-0.613	0.859	0.944	0.339

[a] A measure of compounds that fluoresce near the B(a)p wavelength.
[b] A measure of compounds that fluoresce near the naphthalene wavelength.

Table 43. Correlation matrix of chemical analytes, mixed-function oxidase enzyme activity, and histopathological measures in starry flounder (Platichthyes stellatus) (n=4) (Spies et al., 1985b).

	Sediment									LIVER							
	PAH	tDDT	PCBs	Cd	Cr	Cu	Ni	Pb	Zn	PAH	tDDT	DDT (males)	PCBs	PCBs (males)	MFO	MFO (males)	Neoplasia
Sediment																	
tDDT	0.511																
PCBs	0.356	0.985															
Cd	-0.833	-0.751	-0.645														
Cr	0.836	0.718	0.608	-0.999													
Cu	0.875	0.046	-0.123	-0.500	0.519												
Ni	0.774	0.744	0.647	-0.994	0.994	0.426											
Pb	0.832	0.090	-0.063	-0.385	0.393	0.960	0.293										
Zn	0.872	0.808	0.701	-0.986	0.979	0.535	0.967	0.463									
Liver																	
PAH	-0.765	-0.837	-0.753	0.988	-0.980	-0.379	-0.988	-0.284	-0.981								
tDDT	0.227	-0.642	-0.738	0.311	-0.286	0.664	-0.382	0.696	-0.275	0.441							
DDT(males)	0.482	0.941	0.931	-0.570	0.530	0.088	0.535	0.220	0.677	-0.660	-0.464						
PCBs	0.135	-0.507	-0.568	0.436	-0.429	0.524	-0.522	0.662	-0.346	0.522	0.923	-0.229					
PCBs(males)	-0.161	-0.549	-0.554	0.672	-0.673	0.219	-0.745	0.404	-0.573	0.718	0.783	-0.237	0.944				
Liver Index	0.566	-0.150	-0.284	-0.540	0.580	0.651	0.546	0.414	0.439	-0.414	0.313	-0.359	-0.054	-0.346			
MFO	0.441	0.243	0.189	-0.013	-0.011	0.491	-0.087	0.713	0.171	-0.007	0.451	0.534	0.700	0.657	-0.342		
MFO(males)	0.370	0.018	-0.042	0.133	-0.149	0.534	-0.236	0.745	0.014	0.165	0.634	0.325	0.846	0.796	-0.275	0.973	
Neoplasia	0.995	0.423	0.262	-0.787	0.794	0.918	0.725	0.870	0.824	-0.706	0.318	0.403	0.208	-0.097	0.607	0.446	0.398

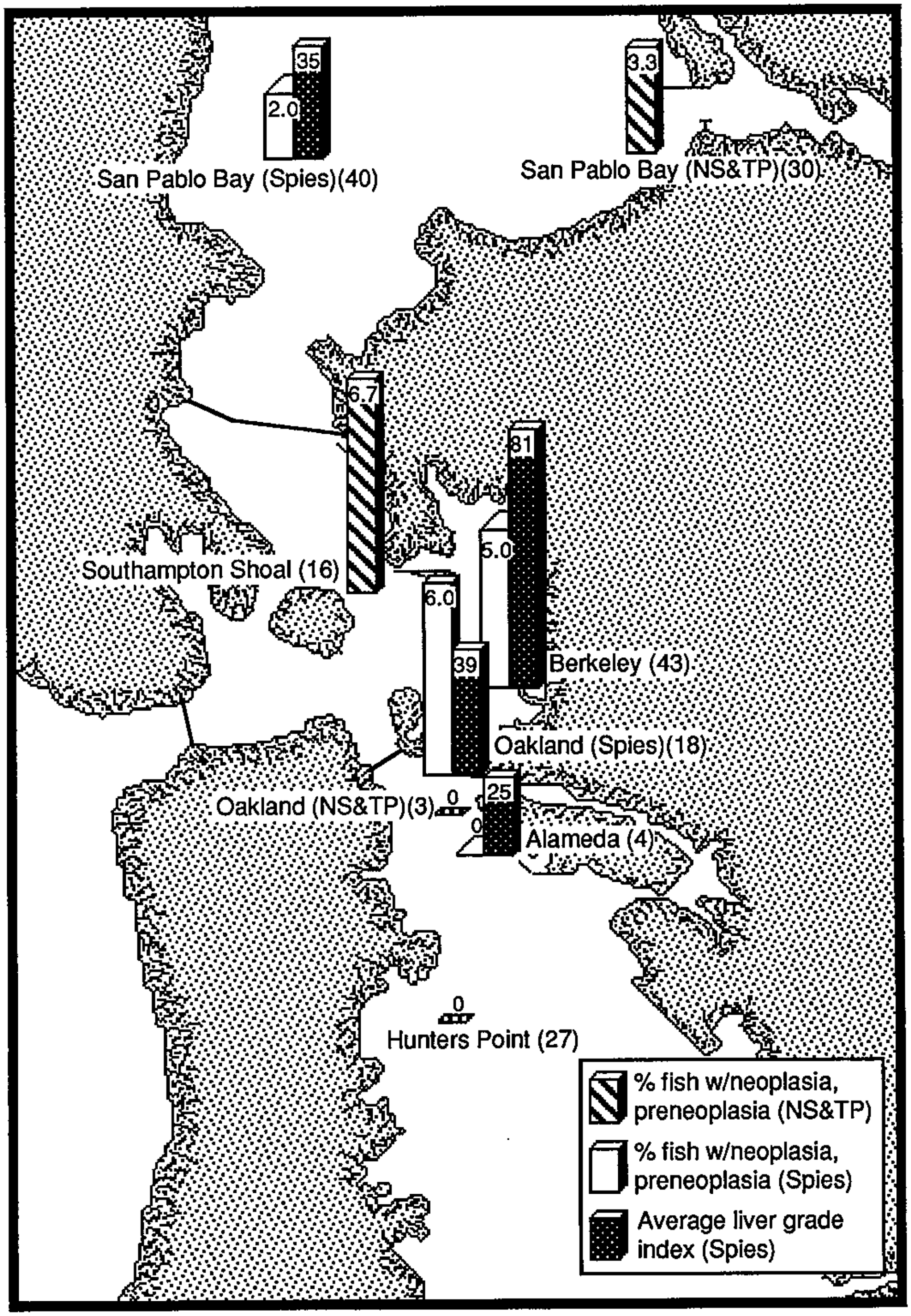


Figure 103. Prevalence of histopathological conditions in the liver of the starry flounder (Platichthys stellatus), 1984-1985, based on data from Spies et al. (1985b) and NS&T Program (NOAA, 1987a); the higher average liver grade index indicates greater occurrence of lesions (number in parentheses is sample size).

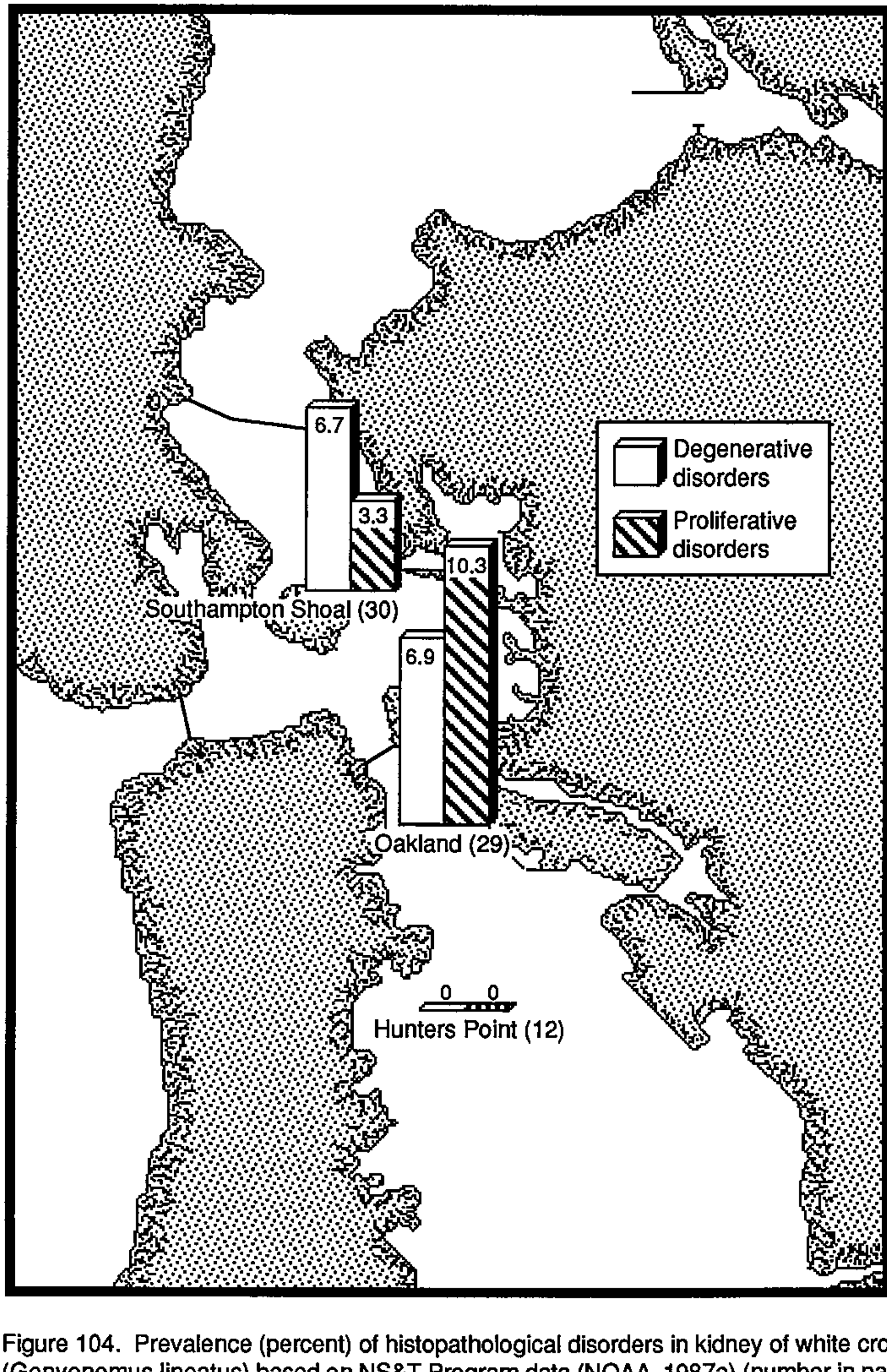


Figure 104. Prevalence (percent) of histopathological disorders in kidney of white croaker (Genyonemus lineatus) based on NS&T Program data (NOAA, 1987a) (number in parentheses is sample size).

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A SUMMARY OF INDICATIONS OF REPRODUCTIVE EFFECTS AMONG STRIPED BASS

Striped bass (*Morone saxatilis*) from New Jersey were initially introduced into San Francisco Bay in 1879. The fishery grew substantially, with established spawning grounds occurring in the Sacramento-San Joaquin Delta east of Suisun Bay. However, studies in the last few decades have reported that the striped bass population has declined dramatically (Stevens, 1977; Jung et al., 1984). The population in San Francisco Bay is 25 percent of what it was in 1962, while egg production is down 90 percent. Suspected causes of the population decline are numerous; no single factor stands alone to explain their demise. Increasing fresh water diversion resulting in entrainment, changing salinity levels, food availability, parasite infestation, and exposure to toxic chemicals have all been considered to be causative factors.

To increase our understanding of the underlying factors contributing to the decline of the striped bass population, NOAA and the California State Water Resources Control Board have sponsored investigations of the sublethal effects of trace contaminants on the San Francisco Bay-Delta striped bass. The project was initiated in 1979 and called the Cooperative Striped Bass Study (COSBS). During the 5 years of the study, 500 striped bass from the Bay-Delta, Coos Bay (Oregon), Lake Mead (Nevada), and the Hudson River (New York) were analyzed for over 325 variables. Topics of the study included bioconcentration phenomena, reproduction and egg fitness, pollutant-parasite relationships, morphological traits, and toxicity studies. Laboratory experiments were also conducted to corroborate observations seen in field-collected fish.

Adult striped bass range annually throughout the Bay-Delta system, spawning in spring in the fresh waters of the Delta or Sacramento River before migrating downstream in summer to the Bay or coastal waters. During this migration they are exposed to numerous anthropogenic contaminants. Table 44 presents the range of contaminant concentrations found in liver, gonads, and muscle of prespawning adults (Jung et al., 1984). With some exceptions, the ranges in concentrations are similar for the three tissues.

The COSBS analysis indicated that the pollutants most implicated in deleterious effects on fish were (in decreasing order): ethylbenzene,1, 2-dimethylcyclohexane, benzene, toluene (all monocyclic aromatic hydrocarbons), DDT, copper, zinc, cadmium, nickel, and mercury. Other pollutants, which were not measured, may also be involved. There were strong associations between these pollutants and decreasing condition (fish length-weight ratio), growth, reproduction, and possibly survival of striped bass.

The mean concentration of monocyclic aromatic hydrocarbons (MAH) in liver and gonad samples are shown in Figure 105 for four sampling sites (Whipple, 1984). The MAHs found in these striped bass are either prime ingredients of gasoline or are used as carrier solvents for pesticides applied to rice fields in the Sacramento Valley. The mean MAH concentrations were highest among fish caught near Carquinez Strait in 1980 and lowest in fish caught near Tiburon in 1978. Evidence suggests that these compounds are detectable only after recent exposures and do not bioaccumulate for long time periods as the chlorinated hydrocarbons do. Since MAHs bioconcentrate and depurate rapidly, acute harmful levels may accumulate leading to cellular damage but depuration processes will result in lower or undetectable levels when the tissues are sampled for analysis in the laboratory. Jung et al. (1984) have correlated the concentrations of zinc and MAHs in the flesh and organs of striped bass with decreasing liver and gonad conditions as well as increases in parasite infection. The concentration of MAHs in ovaries of bass caught in the field (.06 to 6 ppm ww) correlates with concentrations causing decreased egg conditions reported in laboratory experiments (Sakanari et al., 1984).

Egg characteristics and parasite incidence in female striped bass collected by Whipple et al. (1983) from the San Joaquin River near Antioch and the Sacramento River near Clarksburg are shown in Figures 106 and 107. The ratio of gonad weight to total body weight was higher in fish from the Sacramento River than that for fish from the San Joaquin River. Fecundity (total number of eggs) in Sacramento River fish exceeded that of San Joaquin River fish in 1979 by a factor of nearly 2. However, most other measures of reproductive capability appeared to be similar among fish sampled in the two systems.

Striped bass have been afflicted with the parasitic tapeworm *Lacistorhynchus tenuis,* and the roundworm *Anisakis.* In 1979, the California State Department of Health Services issued an advisory on the consumption of raw striped bass muscle, due to roundworm infestation. Whipple (1984) observed an increasing prevalence of tapeworms in San Joaquin River fish from 1978 to 1980. These prevalences were roughly double those seen in Sacramento River fish. Roundworm prevalence was slightly lower in Sacramento River fish. Trends from the same study indicate that from 1978 to 1980, bass from both the Sacramento and San Joaquin Rivers were experiencing slight declines in roundworm infestations. Tapeworm skin lesions appeared to increase slightly in both rivers. The open skin lesions and cellular responses resulting from infestation of the relatively common *L. tenius* have been reported to be unique to San Francisco Bay striped bass.

Research on the striped bass in the Bay continues to the present. More thorough summaries of research results by Whipple and her colleagues are anticipated.

Table 44. Concentration ranges of selected pollutant classes from San Francisco Bay-Delta estuary. Tissue data from adult prespawning striped bass (Morone saxatilis). Tissue concentrations in µg/g (ppm) wet weight for hydrocarbons, µg/g (ppm) dry weight for metals. Data from Whipple, 1984 and Whipple et al., 1987.

POLLUTANT CLASS	CONCENTRATION IN WATER (DISSOLVED) µg/L (ppb)	CONCENTRATION IN TISSUES (ppm) LIVER	GONAD	MUSCLE*
PETROLEUM HYDROCARBONS:				
Total Monocyclic Aromatics	1-200	0.01-10	0.01-10	0.01-7.5**
Total Alicyclic Hexanes	ND	0.02-5.0	0.02-10	0
Total Polycyclic Aromatics	NM	--Whole fish composite =		10
Total Naphthalenes	NM	--Whole fish composite =		0.009
Total Sulfated Thiophenes	NM	--Whole fish composite =		6
CHLORINATED HYDROCARBONS:				
DDT	ND	0.09-0.12	0.10-0.68	NM
DDD	ND	0.10-0.98	0.13-2.8	NM
DDE	ND	0.03-3.1	0.10-12	NM
Toxaphene	0.03-0.32	NM	0.20-2.0	NM
Total PCBS	ND	0.25-13	0.81-13	0.20-4.0
HEAVY METALS:				
Cadmium	0.08-0.20	0.29-9.4	0.08-0.71	0.18-1.3
Chromium	ND	0.61-3.3	0.51-2.2`	0.31-2.2
Copper	1 - 4	1.0-220	1.0-35	0.10-12
Lead	0.03-0.12	0.09-0.37	0.06-0.89	0.11-0.62
Mercury	ND	0.49-13	0.03-0.96	0.06-1.6
Nickel	1 - 6	0.60-1.8	0.37-2.1`	0.50-2.0
Zinc	2 - 6	7.0-250	3.0-310	1.0-66

*Muscle analyses with no skin attached
**Mostly toluene in muscle.
ND = Not Detectable.
NM = Not Measured

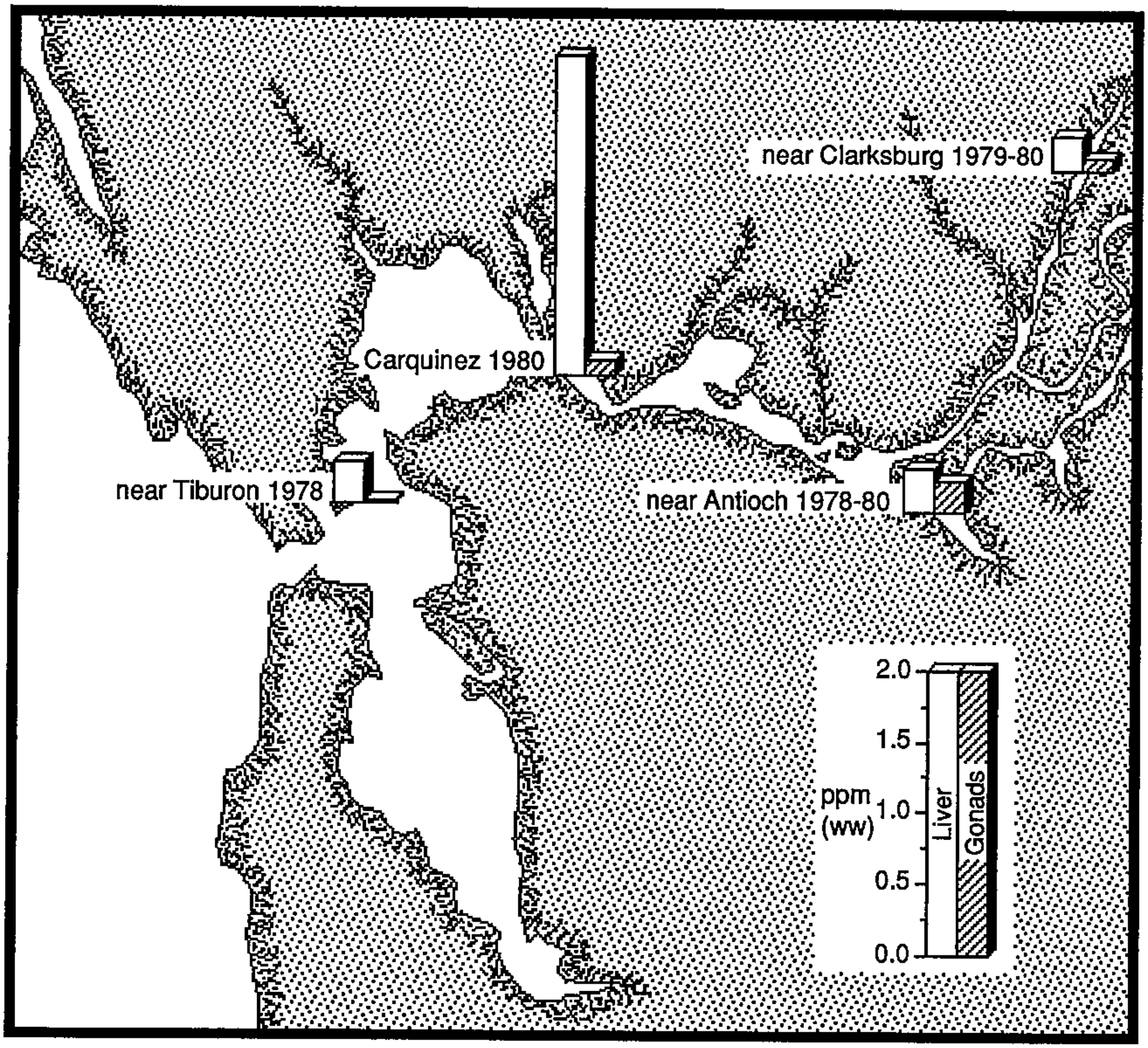

Figure 105. Mean liver and gonad concentrations of monocyclic aromatic hydrocarbons in striped bass (Morone saxatilis) (from Whipple, 1984).

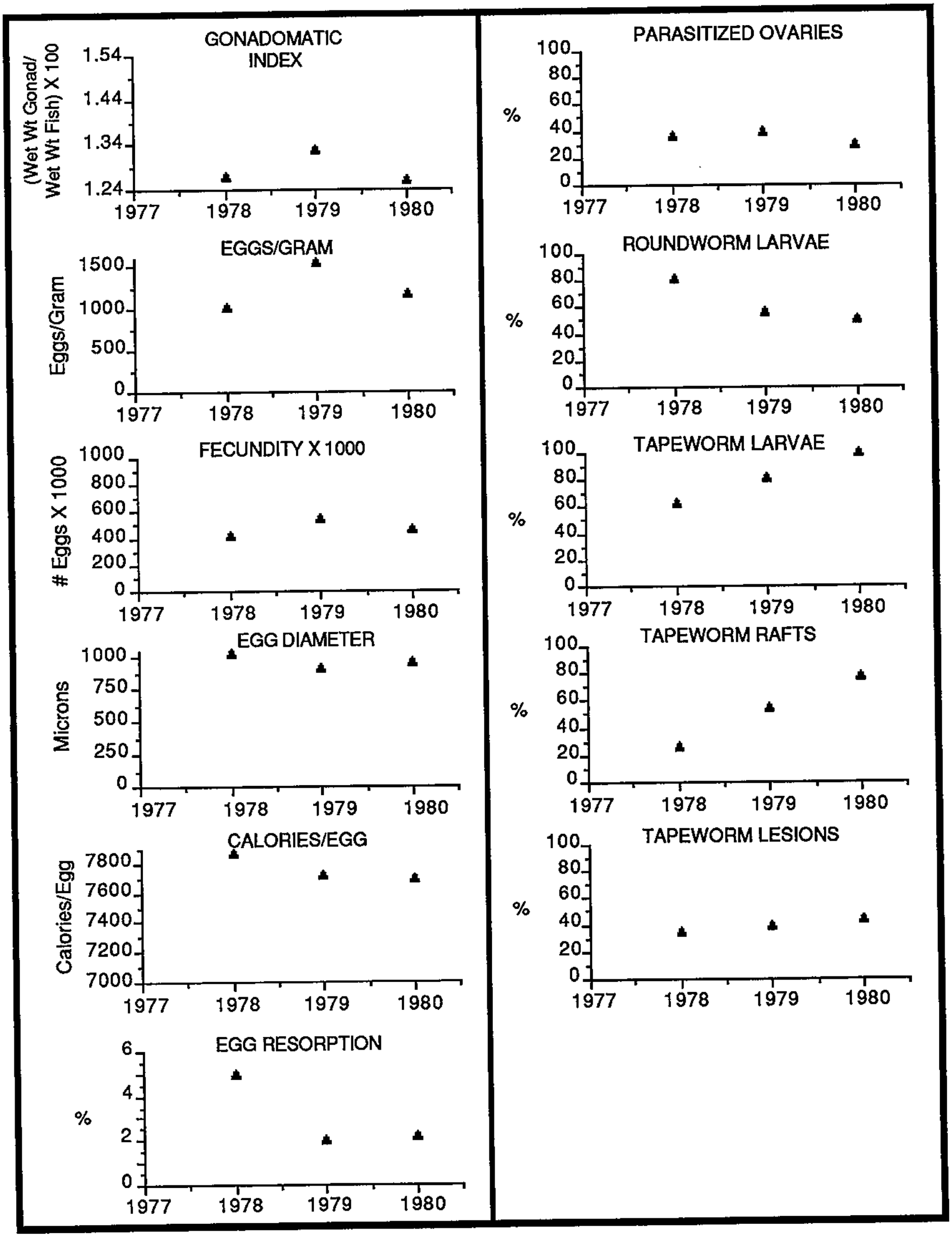

Figure 106. Egg characteristics and parasite incidence in female San Joaquin River striped bass (Morone saxatilis) (from Whipple et al., 1983)..

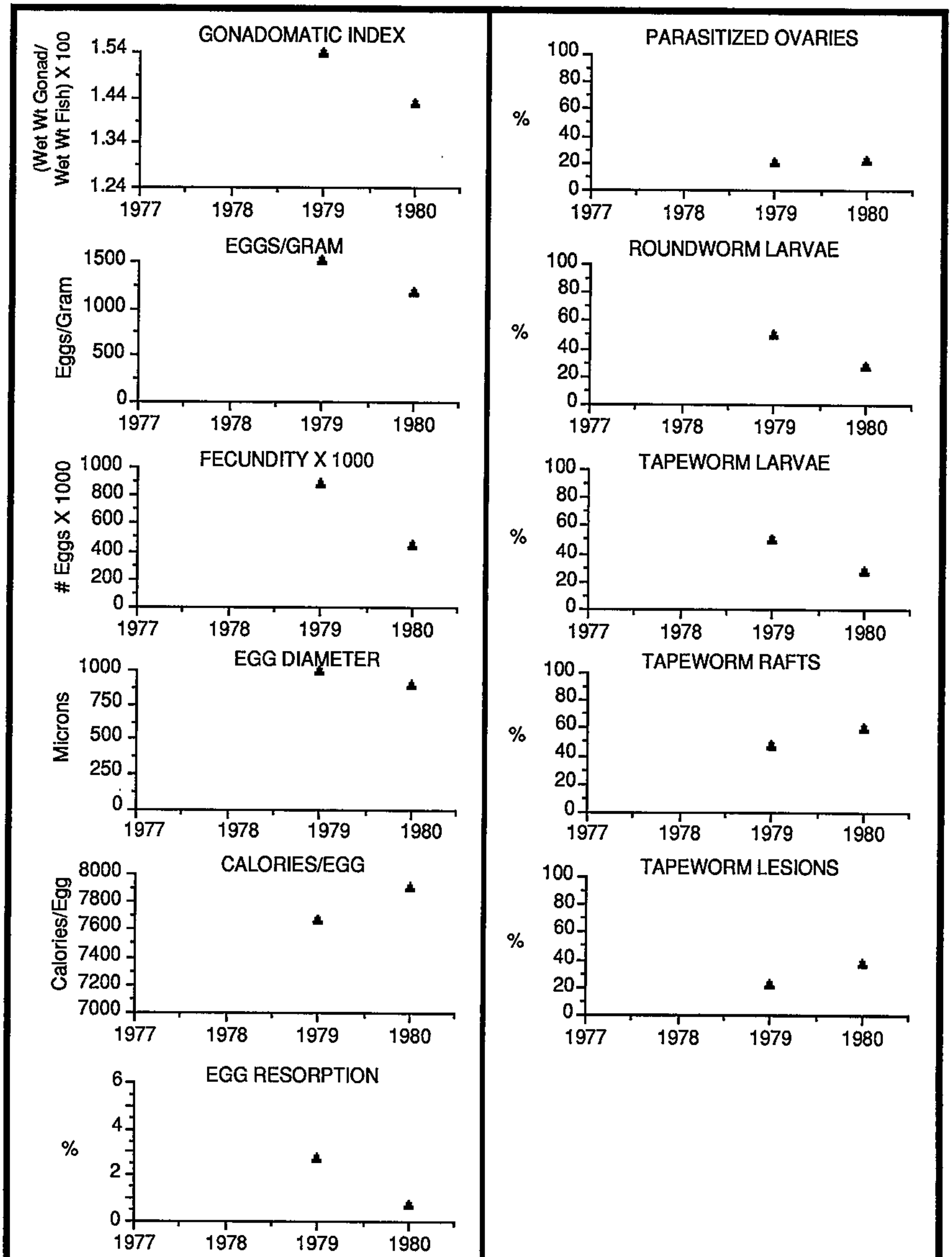

Figure 107. Egg characteristics and parasite incidence in female Sacramento River striped bass (Morone saxatilis) (from Whipple et al., 1983).

A SUMMARY OF INDICATIONS OF REPRODUCTIVE EFFECTS AMONG STARRY FLOUNDER

Indications of effects of contaminants upon reproductive success in starry flounder (*Platichthys stellatus*) have been measured in research performed by the Lawrence Livermore National Laboratory (e.g., Spies, et al., 1985a, b, 1986, in press; Spies and Rice, in press; Rice, et al., in press) supported mainly by NOAA. The research began in 1982 and has continued through 1987. The objectives of the research were to determine the degree, if any, of impairment of reproductive success and the correspondence between measures of reproductive success and other measures of biological health and chemical concentrations. This research has involved development of the necessary laboratory methods, capture of fish from relatively uncontaminated sites and sites where mixtures of organic compounds exist, performance of a variety of analyses indicative of impaired reproduction, and chemical analyses of tissues. Sites throughout the Bay and in other nearby bays have been sampled; attention has been particularly focused upon a relatively contaminated site off Berkeley in central Bay and a site in western San Pablo Bay that is relatively uncontaminated. Various tests and analyses of many hundreds of fish have been performed. Significantly, many of the fish have been spawned in the laboratory to determine fertilization and hatching success.

A. Mixed-function Oxidase Activity

Mixed-function oxidase (MFO) activity was measured in 173 fish captured in the winters of 1982-83 and 1983-84. MFO activity is a measure of the enzymatic response of the fish to exposure to certain organic contaminants and is performed with microsome samples of the liver tissue. The analytical methods for measuring aryl hydrocarbon hydroxylase (AHH) activity are used as a measure of MFO activity. The mean activities were highest in fish collected in the shallow waters off Berkeley, and lowest among fish from western San Pablo Bay (Table 45). Fish in small sample sizes from south Bay, off Oakland, and off Moss Landing in Monterey Bay had intermediate mean activity values. Only the fish collected off Berkeley and in San Pablo Bay were statistically significantly different in MFO activity. These data indicate that fish from the Berkeley site were exposed to higher concentrations of contaminants than those from the other sampling sites.

This enzyme system has an important role in regulating steroid hormone concentrations during gametogenesis and spawning. Since gametogenesis occurs in starry flounders in the fall and early winter months, it is to be expected that MFO activity would be reduced then to avoid metabolism of these hormones when they are needed by the fish. However, MFO activity may not be suppressed in fish that are simultaneously exposed to organic contaminants. Figure 108 illustrates the results of monthly MFO analyses of fish from two sites: San Pablo Bay and off Berkeley. As expected, mean MFO activity was not suppressed at the Berkeley site while it was reduced significantly among San Pablo Bay fish, especially in females. MFO activity in spawning females is generally lower than that in sexually mature females collected from the field early in the stages of gametogenesis.

B. Reproductive Success

Sexually mature females captured at sites in the Bay and induced to spawn in the laboratory have been observed to determine reproductive success. Four measures of reproductive success have been quantified in these starry flounder, each representing a successive step in the sequence of events that occurs in production of progeny. First, the proportion of eggs that float, and thus are viable, is determined. Second, the number of viable eggs that become fertilized is observed, followed by the number of fertilized eggs that hatch (hatching or embryological success). Finally, the proportion of hatched embryos that survive as normal-appearing larvae is determined.

The combined results of these analyses on fish caught in 1982-85 are illustrated in Table 46. In all four stages of reproductive success, the fish from San Pablo Bay exceeded those from the Berkeley site. The differences between sites were significant ($p = 0.001$) for floating eggs and fertilization success, but not for hatching success and normal larvae.

C. Organic Contaminants

The concentrations of organic contaminants in the starry flounder examined for biological analyses in 1984 have been determined in the liver tissues. These data are summarized in Table 47. They indicate that the concentration of DDE, Aroclor 1254, Aroclor 1260, and tPCBs were higher in fish from the Berkeley site than in those from the San Pablo Bay site. The other chemicals were similar in concentrations between the two sites.

The combined concentrations of DDT, DDD, DDE, and all PCB Aroclors in fish captured during 1982-85 are shown in Table 48. Data for both fish sacrificed soon after capture and fish sacrificed in the laboratory after spawning are shown. The data corroborate the between-site differences observed with the data in Table 45; i.e., the fish from the Berkeley site were more contaminated than those from the San Pablo Bay site. However, variability in concentrations within each site is relatively high, a result that is not unusual in a wild population of mobile fish sampled at two sites in the same estuary.

Since these analyses were restricted to those organic compounds that may have a role in diminishing reproductive success, no data exist for other chemicals such as trace metals to compare the two sites. Overall, however, it is apparent from the data generated thus far that the fish from the central Bay site off Berkeley are considerably more contaminated, in terms of mean concentrations, than those from a site in San Pablo Bay.

D. Relationships Between Contamination, MFO Activity, and Reproductive Success

From the data summarized above, it is apparent the samples tested from the Berkeley site were more contaminated, had higher MFO activities, and lower indicators of reproductive success based upon sample means. However, there was relatively high variability, as noted above, among the samples from each site. Extreme values from a few fish could be offset by low values from others in the sample, masking or diminishing site/site differences. Therefore, it is useful to examine the data from individual fish to determine the correspondence or correlation among data from the analyses of tissue contamination, MFO activity, and reproductive success.

The results of correlation analyses performed by Spies and Rice (in press) are summarized in Table 49 and Figures 109 and 110. Decreasing percent viable eggs, decreasing fertilization success, and decreasing embryological (hatching) success were strongly negatively correlated with increasing maternal MFO activity. Percent normal larvae was not correlated with MFO activity. Two additional measures of reproductive success, overall hatching success and overall viable hatch, were also very highly negatively correlated with MFO activity. These latter measures integrate data over several successive stages of reproduction. They represent the proportion of spawned eggs that hatched and the proportion of viable eggs that hatched as normal-appearing, straight-spined larvae, respectively.

Percent embryological (hatching) success was very highly negatively correlated with tPCB concentrations in the eggs (Figure 110, Table 49). Correlations between other measures of reproductive success and PCB concentrations were not significant. Concentrations of other chemicals were not correlated with measures of reproductive success.

From these data, it is apparent that a relationship exists between PCB contamination of eggs, MFO activity of maternal livers, and reduced reproductive success through the embryo hatching stage. Statistical correlations do not equate to determinations of cause and effects. However, other corroborating data from investigations with other species elsewhere support many of the observations made with starry flounder in San Francisco Bay. Several possible mechanisms may explain the relationships between measures of contamination, MFO activity, and reduced reproductive success. First, the contaminants may have a direct toxic effect upon the eggs during their maturation in the parent. Second, increased production of metabolites of contaminants resulting from increased MFO activity may have a toxic effect upon the eggs. These chemicals may bind to macromolecules, including DNA in the liver and gonads, and lower either egg viability or hatching success. These toxic effects may include mitotic aberrations to the chromosomes that eventually lead to reduced viability of the eggs and/or embryos. Third, the amounts or kinds of sex steroids may be altered (e.g., reduced in concentration) by the contaminant-induced high MFO activity, resulting in reduced gamete viability at a critical time in gametogenesis. All mechanisms may be partially responsible simultaneously.

From these studies, it appears that an elevation in MFO activity in starry flounder is a significant indicator of exposure to contaminants and the possibility of impaired reproductive success. It also appears that reproductive success of starry flounder is reduced in some fish, possibly related to contamination, at several stages in reproduction. The fish sampled off Berkeley in central Bay are apparently more contaminated and show signs of greater biological effects than their counterparts to the north in western San Pablo Bay. The ecological significance of these findings to the population of starry flounder in the Bay area has not been investigated.

Starry flounder were sampled during four spawning seasons. There were year-to-year differences in reproductive success and MFO activities. However, since the samples were not equivalent each year, it is not appropriate to attempt to determine temporal trends with the data.

Table 45. Mean MFO activities in feral starry flounder (Platichthys stellatus) from five sites sampled in 1983-84. Sites connected by a line are not different (Tukey-Kramer multiple comparison test ($p = 0.05$) (from Spies et al., 1985b).

	Berkeley, central Bay	Moss Landing Monterey Bay	South Bay	Oakland/Alameda central Bay	San Pablo Bay
n =	54	20	11	15	73
MFO Activity *	95	73	58	54	51

* pmol 3-OH benzopyrene/min/mg protein

Table 46. Reproductive success of starry flounder (Platchthys stellatus) caught in 1982-85 in San Pablo Bay and off Berkeley and induced to spawn (from Spies et al., 1986).

site	Floating eggs	mean percent Fertilization success	Hatching success	Normal larvae
San Pablo Bay(n)	65.9 (19)	73.5 (19)	52.3 (17)	76.8 (17)
off Berkeley(n)	43.1 (18)	51.2 (14)	41.8 (14)	74.9 (14)

Table 47. Concentrations (µg/g lipid weight) of selected organic contaminants in livers of starry flounder (Platichthys stellatus) collected at two sites in August/ September 1984 (means ± standard deviation) (from Spies et al., in press a).

site	n	DDTs				PCB Aroclors				PAHs*
		DDT	DDD	DDE	Total	1242	1254	1260	Total	
San Pablo Bay	15	2.3 ±1.8	2.3 ±0.8	1.5 ±0.5	6.2 ±2.5	1.1 ±1.3	6.2 ±2.2	11.7 ±12.9	19.0 ±13.4	0.1
Berkeley	10	1.3 ±1.6	3.0 ±1.1	2.8 ±0.2	7.1 +4.1	0.6 ±0.8	18.0 ±9.1	41.8 ±23.5	60.3 ±32.1	2.6

*values in µg/g wet wt., not lipid-normalized, n = 1

Table 48. Concentrations of chlorinated hydrocarbons (tDDTs and tPCBs) in livers of starry flounder (*Platichthys stellatus*) collected at two sites (mean µg/kg wet wt. ± standard deviation) (from Spies et al., 1986).

site	n	All field fish	n	Females spawned in laboratory
San Pablo Bay	20	540±300	4	902±732
Berkeley	20	2010±1940	17	2466±1730

Table 49. Correlations between reproductive success measures, hepatic AHH activity, and contaminant concentrations in female starry flounder (*Platichthys stellatus*) collected in San Francisco Bay and spawned in the laboratory[a] (from Spies and Rice, in press).

		Successive stages of survival[b]				Integrated survival	
		% Floating success	Fert. success	Embryo. success	Normal larvae	Overall hatching success[c]	Overall viable hatch[d]
Log AHH	r[e] -0.54		-0.56	-0.66	-0.36	-0.07	-0.58
	P[f]	0.0003***	0.0001***	0.033*	0.68	0.001***	0.001***
Log ΣPCB[g] in eggs	r	-0.035	-0.051	-0.59	-0.18	-0.26	-0.28
	P	0.85	.78	0.001***	0.37	0.17	0.142

[a] Correlations with AHH activity are based on females that spawned with less than 43 days of pituitary injectons. Correlations with PCB measures have been arcsin transformed before regression.

[b] These measures are defined in Rice et al., in press.

[c] The proportion of spawned eggs that hatched.

[d] The proportion of eggs that became straight and normal larvae.

[e] Correlation coefficient, rho.

[f] p for H_0: slope = 0

[g] ΣPCB = Aroclors 1242 + 1254 + 1260.

* -significant, ** -highly significant, *** -very highly significant

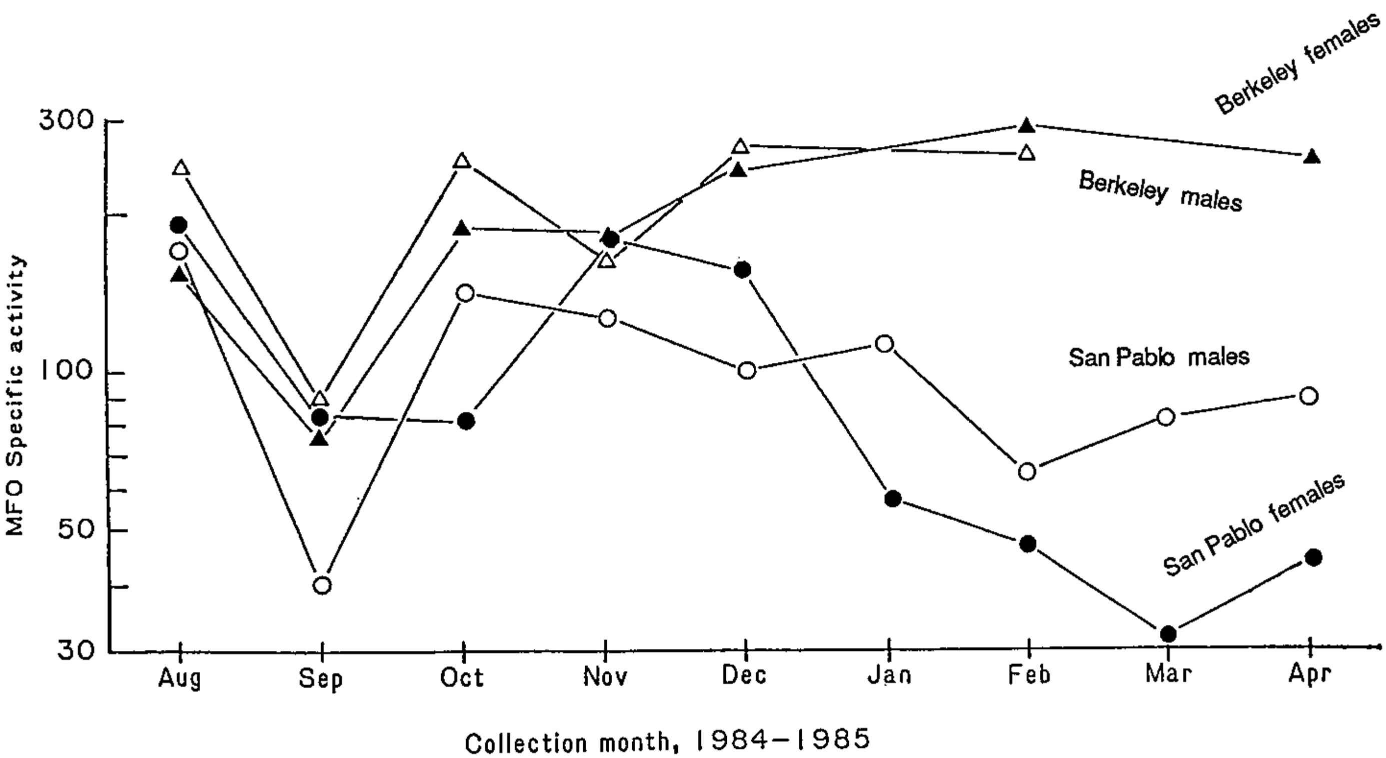

Figure 108. Hepatic MFO activity (pmol 3-OH benzopyrene/min/mg protein) by sex in monthly collections of starry flounder (Platichthys stellatus) from San Pablo Bay and Berkeley. Females with yolky eggs are not included. Triangles are Berkeley collections; circles, San Pablo Bay collections. Open symbols are males; solid symbols, females (from Spies et al., in press).

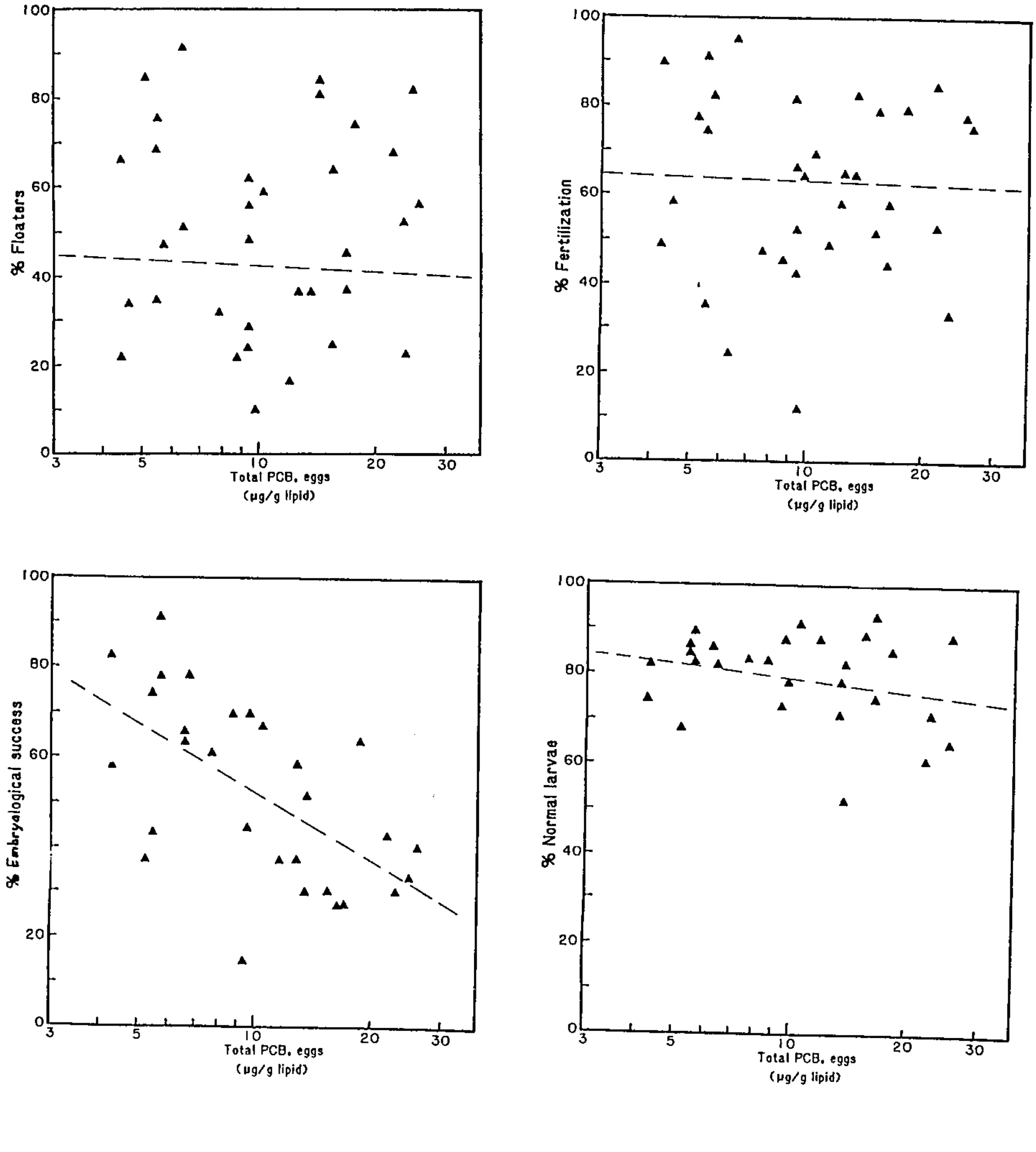

Figure 109. The relationships between tPCB concentrations of spawned eggs and four measures of reproductive success in female starry flounder (Platichthys stellatus) captured in San Francisco Bay and spawned in the laboratory (from Spies and Rice, in press).

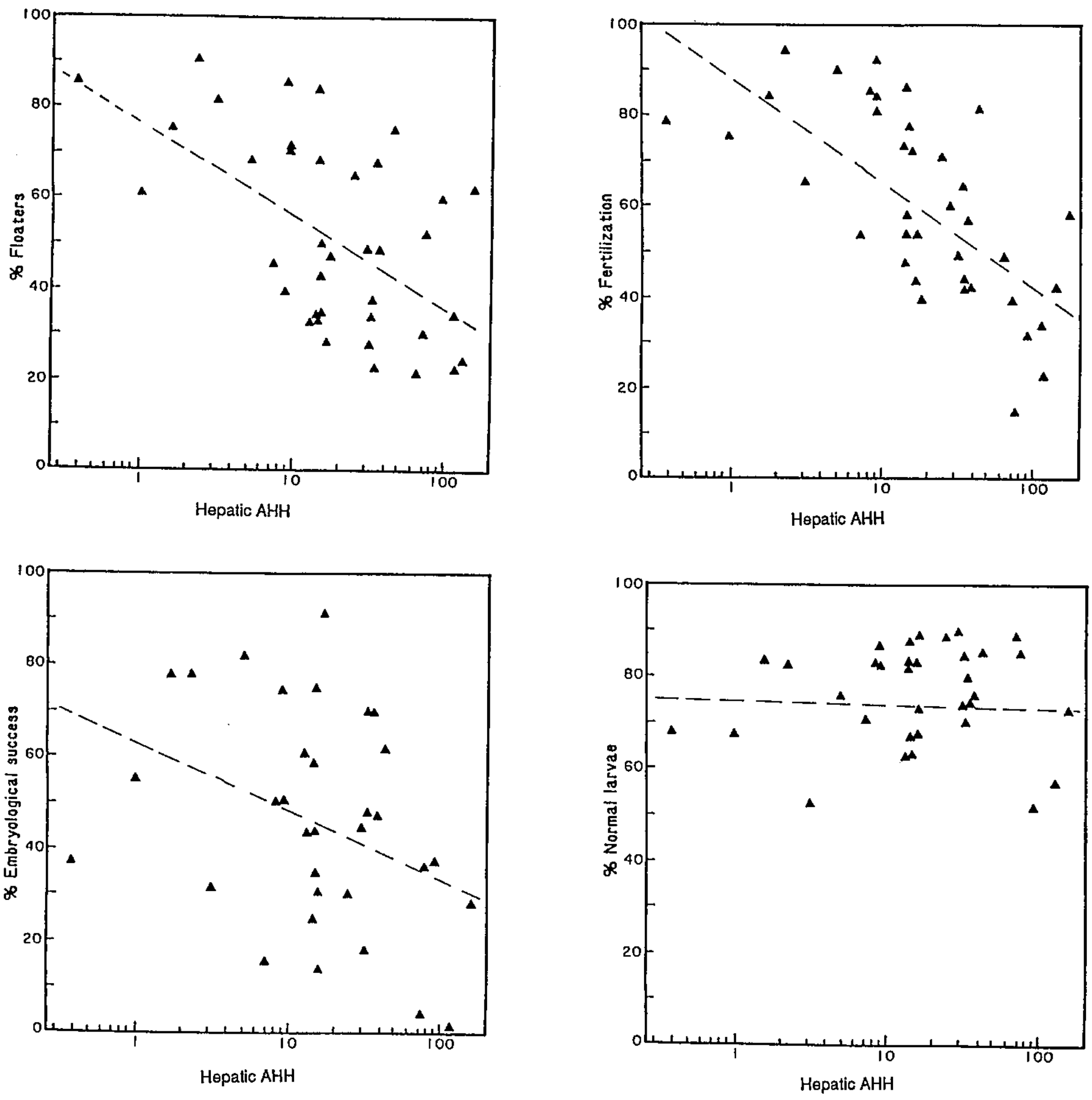

Figure 110. The relationships between hepatic AHH (pmol 3-OH benzopyrene/min/mg protein) activity and four measures of reproductive success for female starry flounder (Platichthys stellatus) collected in San Francisco Bay and spawned in the laboratory (from Spies and Rice, in press).

DISCUSSION AND CONCLUSIONS

The distribution of selected contaminants and measures of biological effects have been documented to widely varying degrees in the Bay. There are considerable data for some chemicals and biological measures and very little for others. Data from many samples exist for some portions of the Bay and very little or none for other areas. There are very limited data regarding biological effects associated with synoptic tests of contamination. There are varying amounts of data for measures of contamination and effects not addressed in this report. Given this situation, the degree of confidence in which the four objectives of this report can be satisfied varies proportionately.

A. Geographic Trends

The concentrations of chemical contaminants in selected peripheral areas and basins of the Bay were compared by examining as much data as possible and identifying trends based upon a preponderance of evidence.

Contaminants are widespread in biota and sediments throughout the San Francisco Bay system. All areas sampled thus far seem to be at least slightly contaminated, i.e., elevated above coastal reference concentrations or above background levels attributable to natural sources. The geographic patterns in the Bay vary from chemical to chemical. There are definite geographic trends for some chemicals, based upon data from analyses of sediments, clams, mussels, and fish. Generally, the highest concentrations of many contaminants occur in the peripheral areas such as harbors, waterways, and boat basins. However, some chemicals are more concentrated in and near the southern end of south Bay, in the Sacramento-San Joaquin Delta, off the Richmond/Berkeley shore or near point source discharges in the basins. For some contaminants, there are no apparent geographic trends; the chemicals are scattered relatively uniformly throughout the system.

There is considerable variation and patchiness in contaminant concentrations in the Bay. Some of the factors that influence this patchiness are discussed later in this chapter. Possibly as a result of patchiness and natural variability, it is difficult to piece together an overall picture of trends for many chemicals despite the large number of samples that have been analyzed. In some cases, trends that are apparent in sediments are not supported by data from the biota or vice versa, thereby precluding the development of a preponderance of evidence.

Generally, within the San Francisco Bay system, the highest concentrations of many contaminants have been found in the following areas: Islais Creek Waterway, Richmond Inner Harbor, Oakland Inner Harbor, Redwood Creek, China Basin, and near the Hunters Point Naval Station. There may be other parts of the Bay that are equally contaminated that have thus far not been sampled or are undersampled. Within the four major basins, many contaminants were often most concentrated south of the Dumbarton Bridge in south Bay, in central Bay off the Richmond/Berkeley shore, and along the western shore of south Bay between Hunters Point and San Mateo. Southwestern San Pablo Bay, north of the navigation channel, was usually low in contamination for most organics and metals, except lead and chromium.

Mercury is relatively uniformly spread throughout the Bay. There is often patchiness among samples within sampling sites in the Bay, whereas mean and median concentrations do not vary considerably among the four basins and many peripheral areas, respectively, of the Bay. There is a pattern of slightly higher mercury levels in peripheral areas than in the basins; mean and median concentrations for sediments have been highest in Coyote Creek, China Basin, Islais Creek, and Guadalupe Slough. Some bivalve samples from the Berkeley Marina, Alameda Yacht Harbor, Redwood Creek, and southern parts of south Bay have had high mercury concentrations. Mean and median concentrations in sediments have been lowest in the central Bay and Carquinez Strait/Suisun Bay basins. Lowest values in mussels have often been observed in central Bay samples. Relative to recently sampled NS&T Program Pacific Coast sites, the Bay has been moderately contaminated with mercury. Among the NS&T Program sites, some of those in the Bay rank among the top ten for mercury levels.

Cadmium is also ubiquitous in the Bay. It is also very patchy in distribution. The highest and lowest sediment concentrations differ by a factor of 865 times. China Basin, Redwood City Harbor, Islais Creek, Coyote Creek, Mare Island Strait, and Guadalupe Slough sediments have been most contaminated with cadmium. Within the basins there may be a pattern of increasing concentrations from north to south in sediments. However, mean and median concentrations in mussels have been very similar among the basins. Some individual mussel samples from Angel Island in central Bay, off Point Pinole in San Pablo Bay, and at the Selby Pier in Carquinez Strait have had high cadmium levels. Clam samples from sites in southern parts of south Bay were relatively contaminated. Very high concentrations were found in fish from Southhampton Shoals. Among the recently sampled NS&T Program Pacific Coast sediment sites, those in the Bay do not appear to be particularly contaminated. The two NS&T Program mussel sites in the Bay were ranked among the top ten in cadmium along the Pacific Coast.

Lead concentrations in sediments have been higher in peripheral areas than in all the basins. China Basin, Islais Creek, Redwood City Harbor, Oakland Inner Harbor, and San Leandro Bay are the peripheral areas with highest mean lead concentrations in sediments. There is no apparent north-south trend in lead concentration among the basins of the Bay. Mussels and clams collected at Point Isabel in central Bay have had especially high lead concentrations. Other areas with high concentrations in mussels have been Alameda Yacht Harbor, Oakland Inner Harbor, and San Leandro Bay. Some clams collected off Berkeley were contaminated with lead. Among the basins, central Bay has had slightly higher lead levels in mussels. Among the NS&T Program Pacific Coast sediment sites, many in the Bay had low concentrations of lead. However, the historical mean concentrations in the Bay sediments and biota were high relative to the recent NS&T Program data.

Chromium is spread throughout the system and, unexpectedly, appears to be more concentrated in the basins than peripheral areas. Mean and median chromium concentrations in sediments have been highest in the San Pablo Bay basin, exceeding those in all sampled peripheral areas. Some individual samples from Mare Island Strait, Islais Creek, south Bay, central Bay, and Oakland Outer Harbor have been most highly contaminated with chromium. Sediment samples from both Bodega and Tomales bays have had high chromium concentrations, also. Chromium concentrations in mussels have been relatively high in samples from south Bay and off Berkeley. Clams from San Leandro Bay have also had high concentrations. No Bay-wide trends are apparent among mussels. Historical levels of chromium in mussels and sediments were not particularly high relative to recent NS&T Program data for the Pacific Coast. However, among the NS&T Program sites, many of the sediment sites in the Bay and those in Tomales and Bodega bays were high in chromium (six in the Bay ranked among the top ten for the Pacific Coast).

A very wide range in copper concentrations (from 1 to 1,500 ppm) has occurred in sediments in the Bay. Mean and median concentrations in sediments have been higher in peripheral areas than in the basins. Those peripheral areas with the highest levels have been China Basin, Mare Island Strait, Islais Creek, Oakland Inner Harbor, and San Leandro Bay. Sediments near the Selby slag site have also had very high concentrations. Among the basins, south and central bays have had the lowest concentrations in sediments. Mean and median copper concentrations in mussels have been very similar among the basins and peripheral areas of the Bay. Many of the individual mussel samples with the most elevated concentrations have been collected in Redwood Creek, Oakland Inner Harbor, Alameda Yacht Harbor, and south of Mare Island. Some samples of clams collected off Albany Hills, Bayview Park, Foster City, Coyote Point, and in Redwood Creek have had high concentrations. Relative to NS&T Program Pacific Coast sites, mussel sites in the Bay have not been and are not highly contaminated with copper. However, three of the NS&T Program sediment sites in the Bay ranked among the top ten along the Pacific Coast in copper levels.

Silver concentrations in sediments have ranged widely (0.01 to 16 ppm), exemplifying the patchy distribution of this chemical. The overall mean and median concentrations in the peripheral areas have exceeded those in the basins by a factor of about 3. Sites in which sediments have had elevated silver concentrations have included China Basin, Islais Creek, Mare Island Strait, Hunters Point Naval Station, and Oakland Outer Harbor. Among the basins, there is an apparent slight south to north decrease in silver levels in the Bay sediments. Mussels in San Pablo Bay have had about half the silver concentrations of those from central and south bays, possibly also indicative of a south to north trend of decreasing concentrations. Mussels from Redwood Creek have had particularly high silver levels. Among samples of clams, those from sites near San Mateo, in Redwood Creek, and off Berkeley have had high concentrations and those from San Pablo Bay have had low levels. Sediments from China Basin and mussels from Redwood Creek have been historically relatively highly contaminated with silver compared to NS&T Program Pacific Coast sites. However, among recently sampled NS&T Program Pacific Coast mussel and sediment sites, the sites in the Bay are not highly contaminated with silver.

Despite their high potential for toxicological effects, very little data exist for PAHs in the Bay. From the available data for sediments, highest concentrations have been observed in Islais Creek, China Basin, and India Basin, whereas the lowest levels were found in samples from San Pablo Bay and Southhampton Shoals. PAH concentrations in crabs collected near Richmond and in Oakland Harbor were much higher than those from coastal reference sites. There are too little data for biota to determine trends within the Bay. However, some samples of starry flounder collected off Alameda had high PAHs. Samples of clams from peripheral south Bay sites had higher PAH concentrations than those from other sites, including those near Richmond. Six NS&T Program sediment sites in the Bay and the historical Bay-wide mean ranked among the top ten relative to PAH levels in the Pacific Coast sites sampled in 1984.

DDT concentrations have been extremely high in mussels and sediments in Richmond Inner Harbor/Lauritzen Canal. They have been relatively high also in parts of central Bay near Berkeley and the Delta, but appear to be relatively low in the remainder of the basins. Historical mean concentrations have been very high relative to NS&T Program Pacific Coast sites, especially in Richmond Harbor/Lauritzen Canal. Among the NS&T Program sites, one mussel site and two sediment sites ranked among the respective top ten for the Pacific Coast.

PCBs are widespread in the Bay. Their concentrations in sediments have been higher in peripheral areas than in the basins. India Basin, Islais Creek, and the Oakland Inner Harbor have had among the highest concentrations. Sediment samples from San Pablo Bay have often had the lowest levels. PCB concentrations in clams have been relatively high at peripheral sites near Richmond, Berkeley, and Oakland in central and south bays. They have also been high in southern areas of south Bay and low in San Pablo Bay. A similar pattern has been observed in mussels. Starry flounder from the Berkeley/Richmond area have also had higher PCB concentrations that those from San Pablo Bay. Among the NS&T Program Pacific Coast sites, three sediment sites and both of the mussel sites in the Bay are among the respective top ten in PCB concentrations. The historical grand means for both sediments and mussels from the Bay were also among the top ten.

The availability of a relatively small amount of data from sediment bioassays precludes any determination of system-wide trends in toxicity in the Bay. The data that are available are mostly from bioassays with amphipods and bivalve larvae. Sediment bioassays have shown that toxic conditions exist in Islais Creek Waterway, off Hunters Point, off Treasure Island, in Alameda Harbor, in parts of south Bay, and off the Port of San Francisco. The degree of toxicity, as judged by the low percent survival or high percent abnormal development in test animals, was unexpectedly high in sediment samples from the Bay. Toxicity in samples from Puget Sound and Southern California Bight with roughly equivalent contaminant concentrations has been much less. Sediment-sorbed chemicals in the Bay may be more bioavailable than those in Puget Sound or off southern California, or they may include toxicants that are not quanitified in routine analytical protocols. Samples from the Pacific Ocean off San Francisco, near the Golden Gate Bridge and in southwestern San Pablo Bay have shown relatively low toxicity.

Impairment of reproductive success in starry flounder, incidence of certain pre-neoplastic and neoplastic conditions, and incidence of high MFO activity have been high in starry flounder collected off the Richmond/Berkeley shore in central Bay relative to those from San Pablo Bay. On the other hand, some pathological conditions have been more prevalent in San Pablo Bay than off Berkeley.

Incidence of skin tumors in English sole has been highest in fish from central Bay, compared to those from south Bay and San Pablo Bay. Neoplastic tumors in livers or "pre-neoplasic" conditions have been observed in low incidences in English sole collected off Berkeley and Oakland and starry flounder at Southhampton Shoal and in eastern San Pablo Bay.

Gonad weight/body weight ratios and fecundity were lower and incidence of parasitism higher in striped bass from the San Joaquin River than from the Sacramento River. Concentrations of MAHs in striped bass were highest in fish from Carquinez Strait.

B. Temporal Trends

There has been no Bay-wide, long-term monitoring program for chemical contaminants and measures of effects in the Bay. The California Mussel Watch Program, USGS, NS&T Program and others have monitored selected chemicals at particular sites for varying periods of time. Much of the data, especially for sediments available from the Bay to portray temporal trends, are from relatively short periods. As a consequence, it is difficult to assess temporal trends in the Bay and the following summary statements can be viewed as hypotheses yet to be tested.

Available data indicate possible recent decreases in concentrations of cadmium, DDT, and PCBs at many sites in the Bay. No changes are indicated with time for mercury, copper, lead, and chromium. Though no data are available to portray temporal trends in silver concentrations in sediments, the data from mussels suggest a decline since 1975 at some south Bay sites. Also, no data exist for determining temporal trends in PAH levels.

No data yet exist to determine temporal trends in sediment toxicity and histopathological conditions, although data for the latter are being acquired by NS&T Program. The data records for tests of reproductive success in fish do not allow tests of temporal trends.

C. Contaminant Levels and Biological Effects

Synoptic measures of contaminant levels and indicators of bioeffects are available for only four suites of measures: benthos community structure, sediment bioassays, histopathological disorders in fish, and indicators of impaired reproductive success in striped bass and starry flounder. The benthos data were not examined in this report.

The sediment bioassay data from Chapman et al. (1986) gathered from only nine stations, showed strong relationships between elevated levels of many contaminants and elevated lethality and sublethal responses. Because three stations in Islais Creek Waterway were especially contaminated with many chemicals and were uniquely very toxic, no single contaminant appeared to stand out as being most correlated with the bioassay responses. All the analytes increased in concentration as the bioassay responses increased. However, the range in the chemical data varied among the analytes from station to station. Significantly, an order of magnitude difference in concentrations of PAHs between nontoxic and toxic stations occurred among the nine stations.

In another study, data from Hunters Point (U. S. Navy, 1987) showed a strong correlation between sediment toxicity and cadmium concentrations in bivalves exposed to the sediments. No strong correlations between sediment toxicity and contamination by organic compounds were observed in sites in south Bay (Baumgartner et al., unpublished manuscript).

The fish histopathology data did not show a strong relationship between contaminant levels in fish and sediments and prevalence of disorders. The relatively low prevalence of these disorders and the ubiquity of contaminants in the basins where sampling was conducted may, in part, explain this observation.

The measures of reproductive success in starry flounder were correlated with the concentrations of chlorinated hydrocarbons in fish. Both the direct measures of spawning success and the measures of MFO activity correlated with tPCBs and total chlorinated hydrocarbons in the fish. These effects were clearly higher in fish captured near Berkeley and Oakland than in their counterparts from San Pablo Bay and elsewhere in the Bay. Decreased liver and gonad condition in striped bass has been correlated with high MAHs in the fish. The concentrations of these hydrocarbons in the ovaries of field-caught fish correlates with concentrations causing decreased egg conditions in laboratory experiments.

D. Representativeness of NS&T Program Sites

All except one of the NS&T Program sites in the Bay have been or are in the basins. The intent of the Program was to track conditions in areas that integrate inputs from multiple sources. The Program was not intended to monitor conditions attributable to single point sources. Therefore, sites in the Bay were placed at many locations ranging from near the Dumbarton Bridge to near Vallejo to provide a representation of conditions in the many hydrographic/pollution regimes of the system. The basins appear to integrate inputs from municipal sources, industries, runoff from urban and rural sources, and spills. Three of the four basins are represented with NS&T Program sampling sites.

Table 50 presents a comparison of the mean sediment and mussel values for the nine analytes examined in this report from the NS&T Program sites in the Bay versus the mean values calculated from the historical data from the respective basins in which the sites were located. In this table, the data from the San Mateo Bridge NS&T Program site, for example, are compared with those from the overall mean for south Bay. The "x" indicate the mean NS&T Program values and the historical basin mean values were within a factor of 2 of each other, and therefore, agree relatively well. The designations "low" and "high" indicate the NS&T Program values were less than half or more than twice the basin mean values. This comparison is performed despite the fact that the basin means are largely from historical data that predate the NS&T Program data and the former are calculated based upon data from many sites in each basin, including those near combined sewer/storm overflows and discharge point sources, all of which were avoided by the NS&T Program. These differences are especially important for sediment data.

From the sediment data in Table 50, it is apparent that only the silver values at the Southhampton Shoal site are similar to the basin mean for central Bay. At the Hunters Point site, only the copper, lead, and silver values are similar, in this case, with the south Bay basin mean. For the remaining sediment sites, there was good agreement for either four or five of the analytes for which comparisons could be made. All but one of the sites were relatively low in cadmium levels relative to the respective basin means, possibly reflecting the temporal decreases seen in this chemical. Chromium at four of the sediment sites was more than twice the respective basin historical mean. Agreement was very good for the silver data.

For the San Mateo Bridge and Dumbarton Bridge mussel sites in south Bay, it is apparent the site means are similar to the respective basin means for six and five analytes, respectively. The data from these sites were relatively low for lead as compared to the south Bay basin mean.

Overall, from the comparison above, it appears that the data from NS&T Program sites in the Bay are relatively similar to the mean values calculated from historical data. Spatial heterogeneity and short-term temporal (e.g., seasonal) processes are sufficient to cause variability in the concentrations of some contaminants. However, some of the sites adequately detected some of the well-documented contaminant signals for parts of the Bay. For example, the San Mateo Bridge sediment site and the Dumbarton Bridge mussel site reflected the high silver and PCB concentrations observed by others in south Bay. The San Mateo Bridge mussels also reflected the south Bay PCBs, but not the silver. The sediment sites off Point San Pedro in east San Pablo Bay, and off Semple Point showed high chromium levels previously observed in San Pablo Bay. The high PCB concentrations known to occur off Berkeley were reflected in the Yerba Buena Island and Oakland sediment sites, but not in the Southhampton Shoal site.

The NS&T Program collects mussels at sites previously sampled by others. A relatively long record of contaminant concentrations, therefore, can be assembled for some analytes. Where NS&T Program data collections have been performed at sites sampled previously by other groups, the NS&T Program data largely provide comparable data. The data are for many of the same analytes and reported similarly. The data reported by the NS&T Program are mostly in the same range as that reported by others sampling the same site and media. The data can be confidently used to extend the temporal trends records. The notable exceptions are PCBs and DDT. The PCB data from Bodega Head mussels sampled in 1986 were an order of magnitude higher than observed by others over a 10-year period at the same site. The NS&T Program sediment sampling sites are not located where previous sampling has occurred. Some of the sites sampled in the Pollution Distribution Study and analyzed for lead, copper, cadmium, and mercury were near some NS&T Program sites, but not near enough to warrant comparing the data. The DDT concentrations reported for Mussel Watch sediment sites in the Bay are similar to those reported by Spies and associates, but both investigations report values an order of magnitude higher than those of the Benthic Surveillance Project and the Sediment Quality Triad Study.

E. Relationships Between Sediment Physical-Chemical Properties and Contamination

One of the objectives of analyzing sediments is to determine the degree of contamination of a site or area relative to other sites or areas and/or relative to source loading rates. However, many factors, other than patterns in loading rates to a receiving system may influence or control the degree of contamination of the sediments. Heavy metals and organic compounds initially enter the estuary in the water column either in dissolved form or associated with suspended particulate matter in the water column. Some portion of the contaminant load eventually settles out in areas where water velocity is low. The contaminants may enter the sediments by either being sorbed directly by the sediments at the sediment/water interface or by being sorbed to suspended particles before they settle out. Once in the sediments, they may be partitioned among several different phases (sorbed to sediment particles, sorbed to organic matter, sorbed to hydrous iron or manganese oxides, exist as discrete minerals, or occur in crystal lattice positions) depending on the physical and chemical composition and environment of the sediment (de Groot et al., 1976). These physicochemical characteristics of the sediment can influence concentrations of chemical contaminants in the sediment. Therefore, some of the physicochemical characteristics that can affect the concentrations of contaminants in estuarine sediments are: the oxidation-reduction state of the sediments, the grain size (texture), the amount of organic matter present, and the concentration of iron and/or manganese in the sediments. In addition, the contaminants can be affected by biological processes and physical disturbance.

Most of the information on the effects of physical/chemical processes on contaminants in sediments in the Bay is for heavy metals. Therefore, the following discussion focuses upon those chemicals, although some of the same processes may also influence organic compounds.

When sediments are initially deposited they are generally in an oxidative state that allows for the formation of heavy metal complexes with iron and manganese oxides. But, as this initial layer of sediment becomes buried by newly deposited layers, it changes to a reduced state. In the reduced state, the heavy metals that were complexed with iron or manganese oxides will either be released to the interstitial water or will form sulfide complexes (de Groot et al., 1976). In oxidized sediments, the iron and manganese oxides will compete with each other and with the organic matter for the binding of heavy metals (Luoma and Bryan, 1981). Therefore, the higher the concentrations of iron and manganese oxides and organic matter in oxidized sediments, the more binding sites there are for heavy metals, resulting in higher heavy metal concentrations.

Grain size is generally related to the mineralogical and chemical composition of sediments (de Groot et al., 1976). The minerals composing the the finer grained sediments (silts and clays) generally have a greater affinity for adsorbing heavy metals than do the minerals composing the coarser grained sediments (sands) (de Groot et al., 1976). "However, the strength of metal association with clay surfaces is weak relative to metal associations with substrates which would compete for binding in oxidized sediments. Thus, the most likely role of clays in such sediments is that of a carrier for substrates which bind metals more strongly" (Jenne, 1977 in Luoma and Bryan, 1981). Therefore, as grain size decreases, the surface area for metal-binding substrates (e.g., Fe and Mn oxides) increases, and the sediment's capacity for binding heavy metal increases.

As indicated above, many interrelated "natural" factors other than loading rates, can affect heavy metal concentrations in sediment. In the interpretation of data, such as those in this report, a question often remains regarding a determination of what percent of differences or changes in heavy metal concentrations is due to differences or changes in loading rates and what percent is due to differences in the physicochemical characteristics of the sediment. One method used to relate the influence of these factors to contaminant concentrations is a regression analysis. A regression analysis of metal concentration versus a sediment characteristic can be done, but the results must be viewed with caution because "a statistically significant regression may imply a chemical relationship within sediments although such a correlation may also occur if metals and substrates are deposited simultaneously... or if a third variable (e.g., particle size) correlates with both variables" (Luoma and Bryan, 1979).

From the summer of 1983 through February 1986, Luoma et al. (1987 manuscript) sampled subtidal sediments from nine stations in Suisun Bay and the Sacramento-San Joaquin Delta. Sediment samples were sieved through a 100 µm mesh, and the portion of the sediments passing through the mesh were analyzed to determine the concentrations of seven metals, TOC, and the fraction of sieved particles less than 14 µm in diameter. When the sediment samples were predominantly coarse sand, they were analyzed without sieving. When copper, zinc and lead concentrations in sieved samples were correlated to physicochemical parameters (iron, manganese, and TOC concentrations), the correlation rarely explained more than 30 percent concentration variance within a site and explained less than 20 percent of the variance when all the data from all the stations were compared. The physicochemical characteristics had no statistically detectable influence upon cadmium concentrations. "Although fluctuations in sediment characteristics may have caused some natural variability in metal concentrations, fluctuations in metal concentrations that occurred independent of the sediment characteristics were common" (Luoma, et al., 1987 manuscript).

Since sediment particles can both adsorb trace metals directly, as well as supply surface area for the retention of metal-sorbing substrates, grain size and/or surface area are often used to correlate metal concentrations. Mayer and Fink (1980) performed a regression analysis of chromium concentrations in three relatively unpolluted rivers in Maine to two grain size fractions (<63 µm and <16 µm) and to surface area. They found that the correlation coefficient (r^2) for the <63 µm fraction ranged from 0.08 to 0.95, the $r2$ for the <16 µm fraction ranged from 0.84 to 0.94 and for the surface area it ranged from 0.80 to 0.91. Regression analysis on chromium concentrations in the Union River, Maine, showed the r^2 for chromium and the <63 µm fraction was 0.08, while that for the <16 µm fraction was 0.84.They pooled the surface area data and calculated an r^2 value of 0.85. They then plotted chromium concentrations against particle surface area for samples from a river in the same geologic regime that had been heavily polluted by tannery wastes; the chromium concentrations were about two orders of magnitude higher than predicted by the results of the regression analysis of data from the cleaner rivers. Their work demonstrates that the degree of loading can be determined when background contaminant levels and contaminant/physical chemical relationships are known. It also shows one of the problems that can arise when regression analysis is conducted on pooled samples from contaminated and uncontaminated areas; the data from the contaminated sites where loading rates are very important may overpower any relationship that might exist between metal concentrations and the physicochemical characteristics of the sediment.

There are basically two ways of relating metal concentrations to grain size fractions: 1) analysis of the linear relationship between heavy metal concentration and the proportion of the sediment made up of the desired fraction; 2) and fractionation of the sediment sample and measurement of the heavy metal concentration in the one fraction of interest (de Groot et al., 1976). Each method has its advantages and disadvantages. The former method gives additional information on one sedimentological parameter (grain size), as well as the total heavy metal concentration in the sediment. However, it may require collection of numerous samples from any area where sediment properties are patchy. The latter requires only a limited number of samples and provides information for just the grain size fraction (e.g., silt + clay) to which the contaminants are sorbed, but gives no information on overall sediment texture or total metal concentrations that are representative of what is actually in the environment. Since the measurement of grain size is actually an attempt to represent the amount of surface area available for metal-sorbing substrates, Mayer and Fink (1980) recommended that correlating metal concentrations directly to surface area is superior to a grain size correlation. This approach would also eliminate size fraction variability.

The majority of data sets used in the production of this report either did not include data on any of the above mentioned physicochemical sediment characteristics (TOC, iron, manganese, grain size and/or surface area) or contained too few data points to justify regression analysis. The only data set that included at least one of the physicochemical parameters (grain size) of concern and had a sufficient number of data points to justify regression analysis was the Pollution Distribution Survey conducted by the COE in 1973 (COE, 1979a). Figure 111 graphically shows the results of regression analysis for mercury, lead, cadmium and copper concentrations versus percent clay (<2 µm) for 16 samples taken from eastern San Pablo Bay. The analysis was restricted to these 16 sites because they were all in the same general area and were influenced by the same potential metal sources. The results of the analysis indicated a significant correlation between percent clay content, and mercury, lead, and copper concentrations, but there was no clear correlation with cadmium concentrations. As previously mentioned, Luoma et al. (1987 manuscript) also found no correlation between cadmium concentration in the sediments and sediment physicochemical characteristics.

The NOAA NS&T Program data set consists of 51 data points in the San Francisco Bay area, including the two reference sites in Bodega and Tomales bays. The data include information on grain size, TOC, iron, and manganese concentrations. However, the data are derived from a 3-year period and from sites subjected to various rates of pollution loading, and these differences may overpower any differences due to changes in physicochemical characteristics. Table 51 gives the results (r^2) of regression analysis of various analytes versus grain size (percent silt/clay, <63 µm) for various combinations of data points. The r^2 correlation coefficients for the individual analytes vary remarkably, depending on the set of data points used for the calculations. Two of the largest differences are: lead with and without the inclusion of Islais Creek data points (r2 = 21.3 versus 60.3, respectively), and cadmium for all San Francisco Bay data points as opposed to just the Benthic Surveillance data points (r 2 = 0.2 versus 37.4, respectively). When the regression analysis was performed on the data from individual sites, r^2 varied widely, but in most cases, was not significantly reliable due to the small sample size (Table 51).

Another factor that has been found to influence metal concentrations in sediments in San Francisco Bay has been hydrologic events and processes. "Most fluctuations of metal concentrations appear to be related to changes in the hydrologic regime" (Luoma and Thomson, in Thomson et al., 1984). Luoma et al. (1984) found that metal inputs into Suisun Bay were governed by high winter river flows and low summer river flows into the Bay, and that the change was abrupt and affected trace metals in the estuary. Luoma et al. (1987 manuscript) found in Suisun Bay that "the coarsest sediments and lowest concentrations of TOC, Fe or Mn within any year always occurred between April and September (i.e. summer)" and that "in general the highest concentrations of Cu, Pb, Zn and Cd in sediments occurred between December and April, and minimum concentrations occurred during mid to late summer."

The only data set used in this report that had seasonal sampling was the SBDA study in the southern end of the Bay (Stevenson, et al., 1987). Figure 30 (in Chapter 5) displays the within-year variability for copper, with the highest concentrations generally occurring during the January or April sampling period and the lowest occurring during the July or October sampling period. The correlation is not perfect because it would take several years of data to decipher the effects of seasonality due to the frequency and magnitude of year-to-year fluctuations in sediment characteristics (Thomson-Becker and Luoma, 1985).

In conclusion, when comparing sediment contamination data from samples separated either geographical or temporally, the physicochemical characteristics of the sediments must be taken into consideration, and in addition, the hydrologic conditions must be taken into account for temporal comparisons. Most of the data used in assembling trends for this report did not include synoptic measures of the natural sources of variability. Therefore, it was impossible to attribute differences between sampling sites and years to anthropogenic activities versus natural factors. In some cases data reported from grain size analyses were for different size fractions (e.g., <2 µm, <16 µm, or <63 µm), adding further to the confusion. Therefore, any general conclusions drawn regarding temporal and/or geoghraphic trends in contamination of the Bay sediments must be done with caution and with the realization that they may be attributable solely or in part to natural physical/chemical factors.

F. Relations Between Biological Properties of Biota and Contamination

The objective of analyzing the tissues of biota usually is to determine the degree of contamination of a site or area relative to other sites or areas and/or relative to source loading rates. However, many factors, other than patterns in loading rates to a receiving system, and therefore, the concentrations in exposure media, such as water, may influence or control the degree of contamination determined in an animal. Factors that may help explain the natural sources of variability in biota contamination are referred to as normalizers. A very small amount of data exist from measures of biological normalizers that, in part or wholly, explain variations in contaminant concentrations in San Francisco Bay biota. Most of the data expressly generated to examine relationships between normalizing variables and tissue concentrations are for the clam *Macoma balthica* and two or three trace metals. Otherwise, surveys performed in the Bay have generally not included normalizing parameters or have been performed with insufficient sample sizes, precluding the identification of normalizer dependent relationships.

Natural biological sources of variability that may explain geographic and temporal trends in contamination of biota include: animal size, animal age, lipid content, moisture content, stage in gametogenesis, feeding and/or growth rate, and population-level differences in genetics. In addition, the uptake of contaminants can vary with hydrologic, geochemical, and meteorological processes that alter the concentration in the exposure medium (e.g., water, sediments).

California Mussel Watch data (e.g., Hayes and Phillips, 1986) for transplanted *Mytilus californianus* sampled at many sites in the Bay from 1981 through 1986 were examined to determine relationships between concentrations of tDDT, tPCB, and mercury versus lipid concentration and moisture content. The results of a correlation analysis are summarized in Table 52. Sample sizes for each cell of the correlation matrix ranged from 32 to 40. From this analysis, it is apparent that a significant correlation occurred between lipid content and mercury concentration ($F=2.384$, $P=0.02$). Moisture content was positively correlated with mercury concentration and negatively correlated with lipid content. Similarly, data from *Mytilis edulis* at four sites sampled by McCleneghan (1982) show a weak relationship between lipid content and tDDT and a negative relationship between lipid content and tPCB concentration (Figure 112). The sample sizes from this data set are very small and preclude deriving any general conclusions. However, since data from both these data sets are from many sites, relationships between lipids or moisture and contaminant concentrations can be confounded by differences in exposure conditions at each site, i.e., proximity to sources.

The single site for which the largest data record exists for mussels is from California Mussel Watch samples at Bodega Head. However, contaminant levels have been relatively low and monotonous there. Consequently, wide variations in tissue concentrations, and therefore, strong correlations with lipid or moisture content would not be expected. Nevertheless, the plots in Figure 113 indicate the relationships between lipid content and mercury and tDDT concentrations. A positive relationship is indicated for mercury, but not for tDDT at this site.

Data from whole Pacific jack mackerel sampled by Risebrough et al. (1965) in Monterey Bay showed no apparent relationship between lipid content and DDT concentrations (Figure 114).

Stout and Beezhold (1981) did not observe strong positive correlations between biological measurements (length, lipid content) and chlorinated hydrocarbon concentration in most fish analyzed from the northeast Pacific Ocean. The concentrations of DDT/DDD/DDE and lipid content were positively and significantly ($P>0.05$) correlated among white perch, pile perch, and sculpin sampled at two sites in the Bay in 1969 (Earnest and Benville, 1971). Correlations were nonsignificant with shiner perch, English sole, speckled sanddab, and market crab; and correlations were negative with dwarf perch. Bailey and Hannum (1967) showed that among striped bass in Suisun Bay, pesticide concentrations increased with age and crude fat content. The tissue type that was analyzed was not stated.

Data available from Girvin et al. (1975) for resident *Mytilus edulis* sampled in 1974 at 10 sites in the Bay showed negative relationships between shell length and concentrations of mercury, copper, and lead (Figure 115). However, the high metal concentrations in the data set were from small individuals sampled in Islais Creek and Redwood Creek, whereas larger animals were sampled at mostly basin sites. This data set illustrates the difficulty encountered in separating variations in contaminant concentrations due to site location and biological variables when data are from many sites with dissimilar exposure conditions.

Processes that could influence temporal differences in tissue metal concentrations were summarized by Luoma et al. (1985): (1) temporal variability in metal inputs; (2) temporal variability in geochemical characteristics of water and sediments; (3) seasonal fluctuations in tissue mass of the organisms; and (4) temporal changes in dilution, dispersion or other hydrologic characteristics of the estuary. Data were generated in studies in south Bay with two or three metals to assess the effects of the processes on metal uptake by *Macoma balthica*.

Luoma et al. (1985) speculated that all four processes influenced metal concentrations in the Bay. For example, they showed a two-to-fivefold difference in copper concentrations in intertidal *M. balthica* at a site in south Bay over an 8-year record of monthly samplings. Also, their data indicated a system-wide trend of increasing copper concentrations from north to south, presumably related to proximity to sources. They also speculated that freshwater dilution during seasons and years of highest river flow reduced metal concentrations in clams. For example, copper concentrations in south Bay clams have increased in the fall with the onset of occasional showers, reached a maximum between December and March, and declined to an annual minimum in the summer. Luoma and Cain (1979) observed similar patterns with silver, but not with zinc, illustrating the possibility that individual metals behave differently regarding biological uptake. Silver and copper accumulation in clams per unit rainfall was highest in a year when lowest freshwater discharge occurred (Luoma and Cain, 1979). Among the sites sampled, the amplitude of temporal fluctuations was highest where copper concentrations were highest, i.e., in south Bay sites where residence time of water was longest and where the sampling sites were nearest suspected sources. Also, fluctuations can vary in amplitude substantially from year to year at any one site (Luoma et al., 1985). Concentrations declined as salinity declined at a south Bay site, coincident with increased flow of freshwater from the Sacramento-San Joaquin Rivers (Luoma et al., 1985).

Increases in the proportion of suspended sediments that are fine grained during the fall and winter may also result in increased metal availability for filter-feeding clams (Luoma et al., 1985). Mobilization of biologically available copper has been observed in south Bay and other estuaries under anaerobic conditions (Luoma and Cain, 1979).

Seasonal changes in tissue weight often corresponded with metal concentrations (Luoma et al., 1985). Strong and Luoma (1981) and Cain and Luoma (1986) illustrated the complexity of the relationships between clam size and tissue metal concentrations. Size-dependent relationships exist, but they can vary among metals, among size classes, with seasons, and among sites. Strong and Luoma (1981) concluded that four conditions can influence the correlations between animal size and trace metal concentrations. First, metal concentrations may increase more rapidly in small animals than in larger animals during periods of slow growth. However, second, increases in metal concentrations occur more rapidly in larger animals during periods of fast growth, presumably due to a dilution of the metals by additional soft tissues. Thomson et al. (1984) showed that copper was generally more concentrated in large *M. balthica* than in the smaller individuals, especially in the winter. Third, positive correlations between size and metal concentrations are more common than negative correlations, suggesting that net uptake occurs throughout the life of some species. Fourth, some degree of equilibration between tissues and environmental concentrations is suggested by the periodic occurrence of nonsignificant body size-metal concentration correlations.

Luoma et al. (1985) concluded that the quantification of the influences of natural physical and biologic processes is needed to understand the meaning of metal concentrations in indicator biota and the identification of long-term temporal trends can only be determined after seasonal and annual patterns of fluctuation are established.

Foe and Knight (1986) reported seasonal changes in copper and zinc concentrations in caged *Corbicula fluminea* in Suisun Bay. Copper concentrations were roughly two-to-threefold higher in August samples at five sites than in April samples. Zinc concentrations were roughly 1.5 times higher in August samples than in those collected in February and April. These differences were not due to changes in concentrations of ingested sediment-bound metals in the gut. Rather, the authors concluded that the differences represented actual increases in tissue concentrations.

It is apparent from the discussion above that a complex multitude of processes influence contaminant concentrations in biota in addition to the concentrations of contaminants to which the biota are exposed. The effects of these processes on tissue concentrations are likely site-specific and contaminant-specific. Therefore, any general conclusions drawn regarding both temporal and geographic trends in contamination of biota in the Bay must be done conservatively and cautiously and with the realization that they may be attributable solely or in part to natural factors.

Table 50. Comparison of mean NS&T Program sediment and mussel site values and respective historical mean basin values. Marks (x) indicate the two means were roughly within a factor of 2 of each other; "low" and "hi" indicate the values were less than half or more than twice, respectively, the historical mean values; "n/a" indicates insufficient data available to calculate historical basin means.

Site	Hg	Cd	Cu	Pb	Cr	Ag	PAH	DDT	PCB
				Sediments					
Semple Point	low	x	x	x	x	low	n/a	n/a	n/a
E. San Pablo	x	low	x	low	x	x	low	n/a	n/a
Pt. San Pedro	x	low	x	x	x	x	n/a	n/a	n/a
S'hampton Shoal	low	low	low	low	hi	x	n/a	n/a	n/a
Yerba Buena Is.	x	low	x	x	hi	x	n/a	n/a	n/a
Oakland	x	low	x	x	x	x	n/a	n/a	n/a
Hunters Point	low	low	x	x	hi	x	n/a	n/a	n/a
San Mateo Br.	x	low	x	x	hi	x	n/a	n/a	n/a
				Mussels					
San Mateo Br.	x	x	x	low	x	low	n/a	x	x
Dumbarton Br.	x	x	x	low	low	x	n/a	hi	x

Table 51. Percent correlation of analyte concentrations to percent silt/clay (<63µm) based on regression analysis of NS&T Program data from NOAA, 1987a; Boehm et al., 1987; and Chapman et al., 1986 ($p \leq 0.01$).

Analyte	All SF Bay Area NS&TP Data	SF Bay NS&TP Data	SF Bay NS&TP Data w/o Islais Creek	SF Bay Benthic Surveillance	Southhampton Shoal	Hunters Point	East San Pablo Bay	Oakland	Bodega Bay
Mercury	5.4	3.9	1.8	1.8	**92.4**	63.8	15.7	3.1	15.0
Lead	**23.7**	**21.3**	**60.3**	**42.7**	38.7	7.7	56.3	30.6	58.5
Cadmium	0.4	0.2	3.7	**37.4**	66.9	67.5	**86.2**	17.6	0.0
Chromium	**22.5**	**22.6**	**20.0**	0.8	4.7	15.1	44.7	21.6	24.9
Copper	**53.1**	**48.2**	**53.7**	**45.6**	10.9	7.9	5.0	28.0	81.5
Silver	4.7	8.3	2.8	13.1	26.0	73.0	5.4	10.1	83.4
tPAH	11.1	10.0	6.6	4.1	22.5	27.1	41.2	0.5	50.6
tDDT	**18.0**	**18.2**	**22.0**	24.2	22.6	52.9	**85.4**	12.7	27.6
tPCB	**19.1**	**20.3**	**22.7**	**32.3**	5.5	5.5	21.5	23.5	43.7
Aluminum	0.7	0.1	0.9	2.0	**96.4**	22.4	18.4	10.3	3.8
Iron	**41.9**	**29.9**	**29.9**	21.0	0.7	17.9	0.5	63.6	37.9
Manganese	0.7	6.8	3.5	14.1	11.6	0.9	31.8	16.3	53.4
n=	*51*	*42*	*39*	*21*	*6*	*6*	*6*	*6*	*6*

Table 52. Correlations among lipid content, moisture content, and concentrations of DDT, PCB, and mercury in *Mytilus californianus* transplanted by California Mussel Watch (e.g., Hayes and Phillips, 1986).

	lipid	% water	tDDT	tPCB	Hg
lipid					
% water	-.656*				
tDDT	-.053	-.032			
tPCB	.081	-.158	.12		
Hg	-.409*	.588*	-.249	.076	

* indicates significant correlation at p = .02

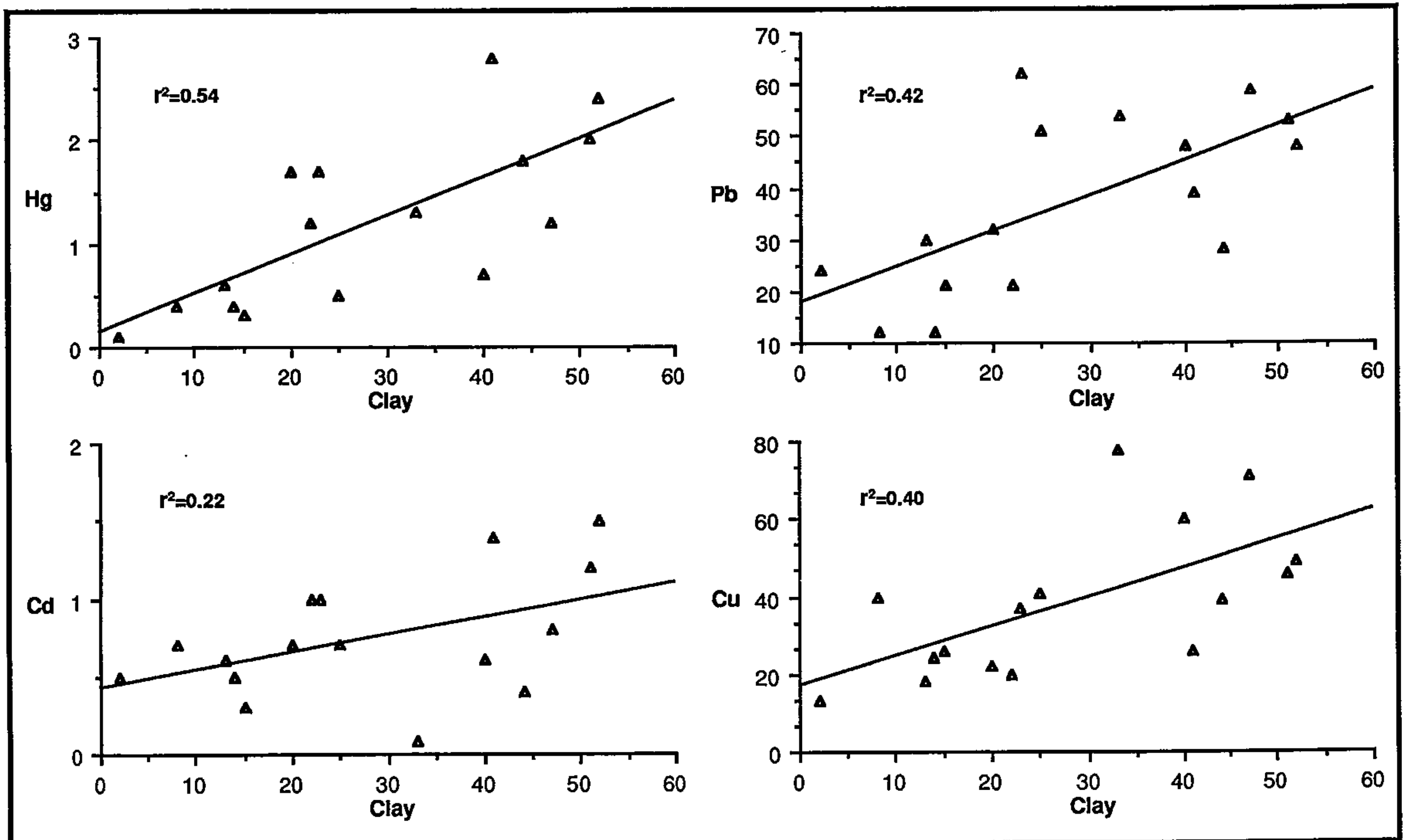

Figure 111. Regression analysis of mercury, lead, cadmium, and copper concentrations, in ppm dw, versus percent clay from 16 sites sampled in San Pablo Bay in 1973 by the COE (1979a). In all but the cadmium analysis $p<0.01$; for cadmium $p=0.06$.

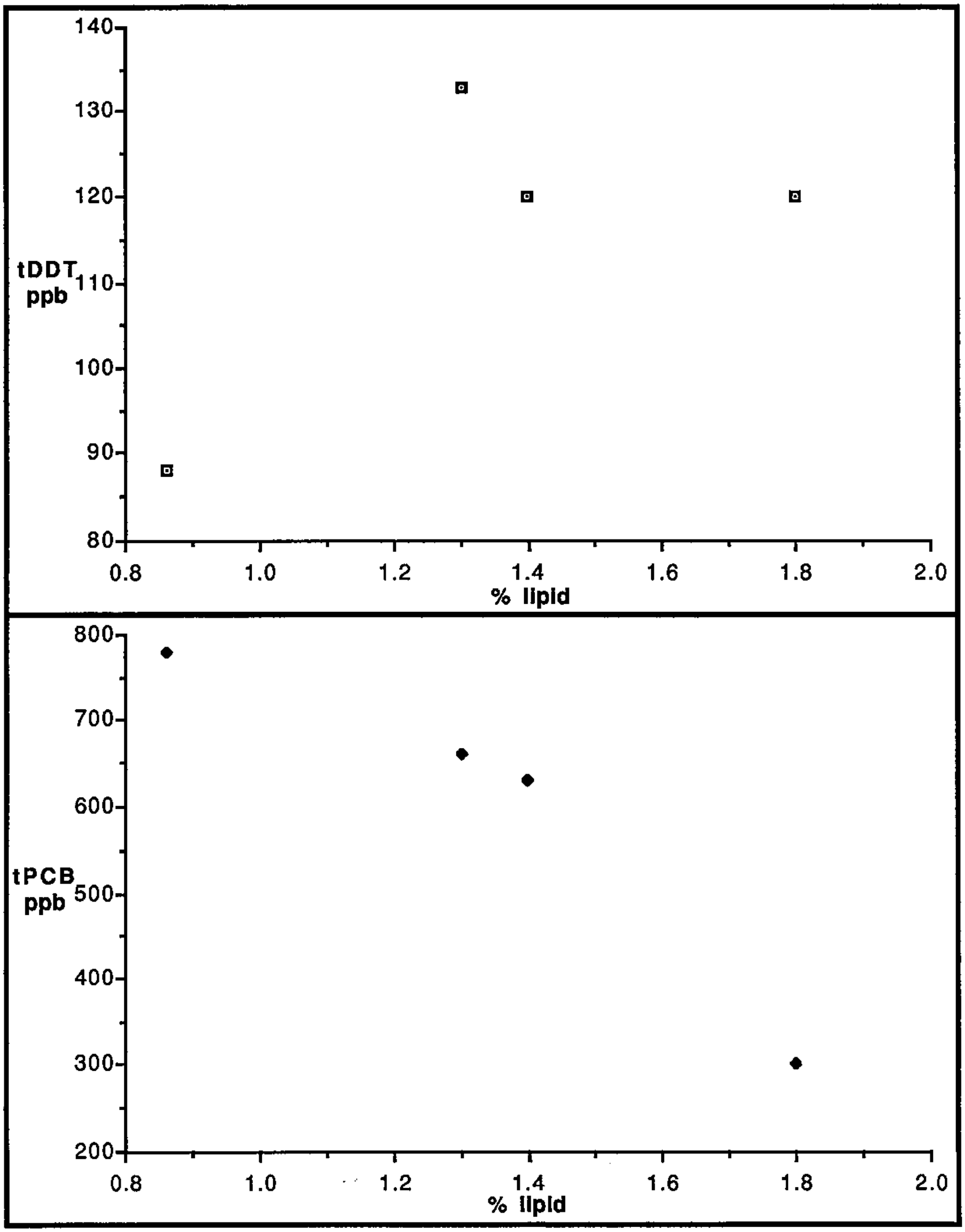

Figure 112. Scatterplots of lipid content versus DDT and PCB concentrations in Mytilus edulis at four sites in San Francisco Bay (from McCleneghan, 1982).

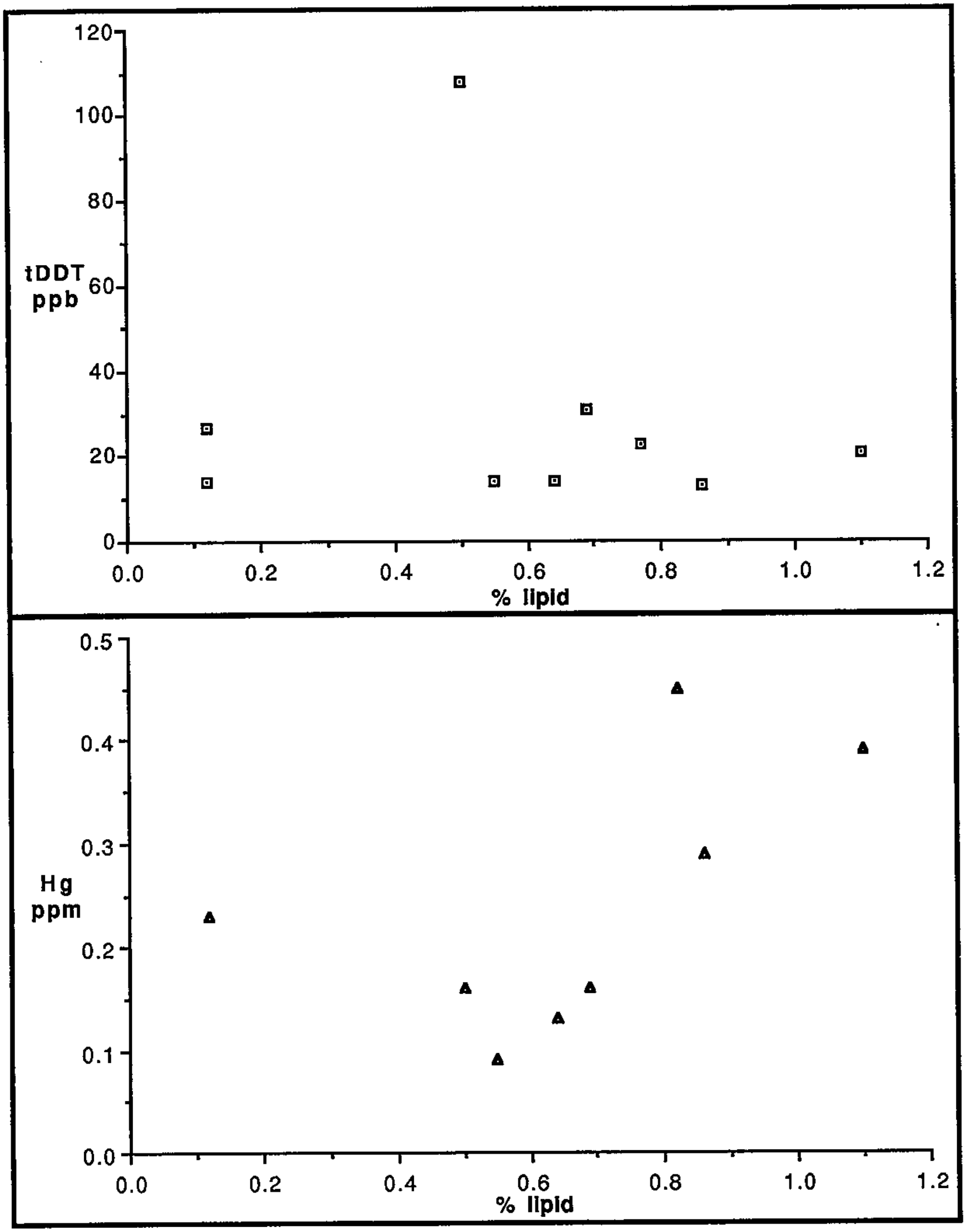

Figure 113. Scatterplots of lipid content versus tDDT and mercury concentrations in Mytilus californianus sampled at Bodega Head by California Mussel Watch (e.g., Hayes and Phillips, 1986).

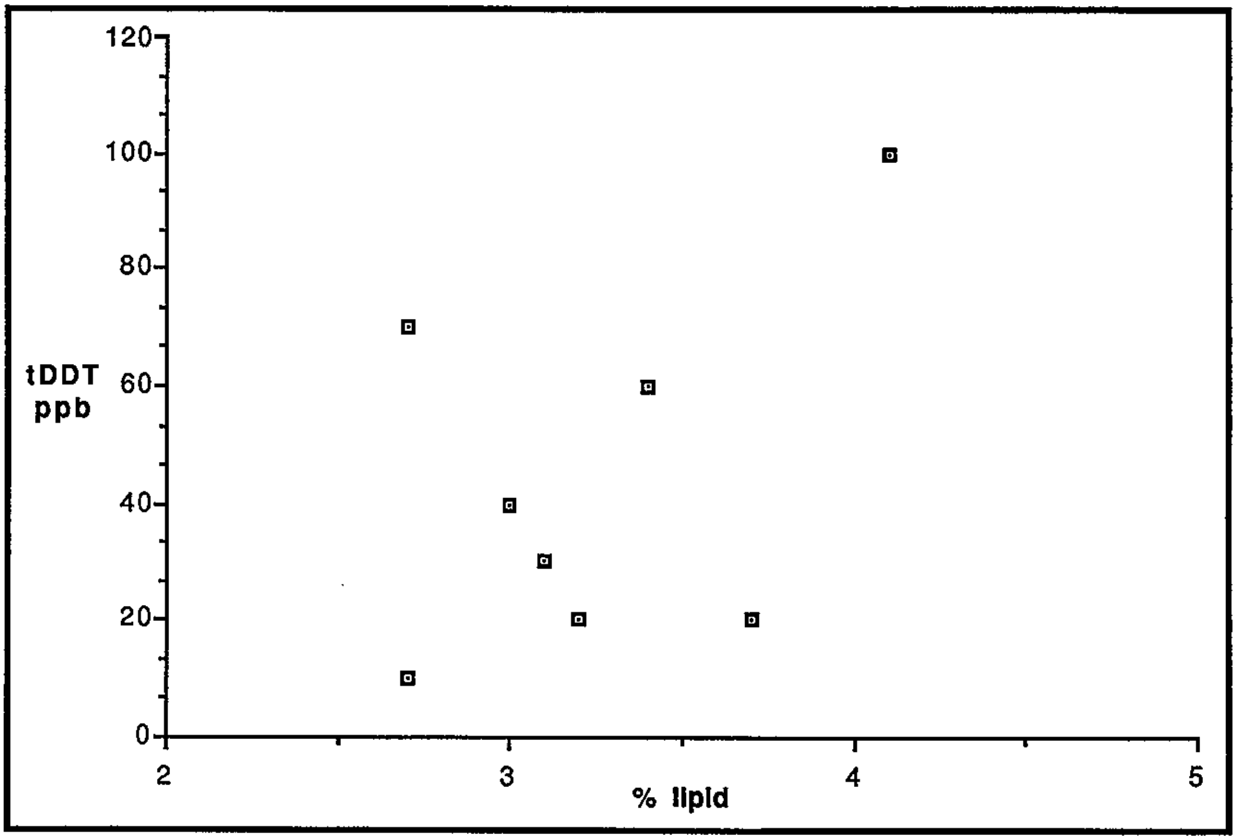

Figure 114. Scatterplot of lipid content versus tDDT concentration in whole Pacific jack mackerel sampled in Monterey Bay by Risebrough et al. (1965).

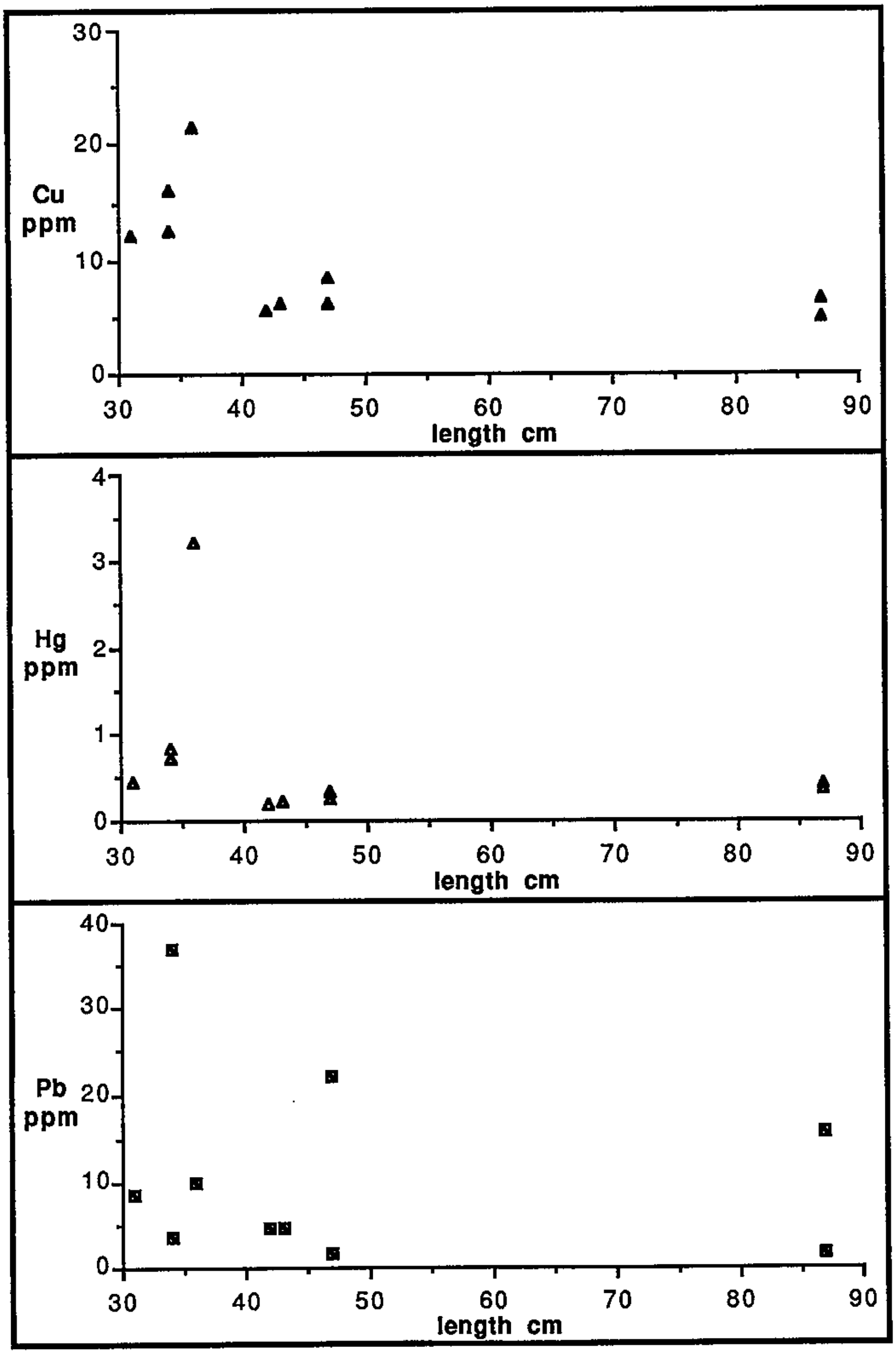

Figure 115. Scatterplots of length versus copper, mercury, and lead concentrations in *Mytilus edulis* sampled at 10 sites in San Francisco Bay by Girvin et al. (1975).

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